Bournemouth University

An investigation into the use of inertial measurement units to assess the loading profiles of adolescent Badminton players.

by

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Abstract

Monitoring athlete loading is important for understanding athlete adaptations, recovery and injury risk. It is common practice to calculate training load from trunk-mounted accelerometers, housed within Inertial Measurement Units (IMUs), yet many sports have specific anatomical regions where higher loads or injuries occur, which may not be measurable through trunk-mounted IMUs. Badminton was selected for study due to the high prevalence of both lower limb injuries and asymmetries. The aim of this thesis was to provide insights into the use of IMUs for the assessment of training load, measurement of movement asymmetries and in return to training protocols within adolescent Badminton players.

This work established the reliability and validity of upper trunk-mounted IMUs for assessing the training load of Badminton-specific movements. While acceptable levels of reliability were found between IMU systems, higher levels of reliability were recorded when the same brand of IMU system was used. However, axis-specific training loads from a single upper trunk-mounted IMU were found to be poorly correlated to both overall and lower limb-specific RPE. These findings suggested that IMU placement nearer or directly on the lower limb (tibia) as the area of investigation may provide greater insights regarding lower limb loading.

To understand the potential limitations of IMU placement locations, racket sport coaches were surveyed and found to support the use of IMUs to assess loading in training but not in competition, with a number of IMU placements receiving positive responses, including

at the tibia. Training load from tibia-mounted IMUs was then found to differentiate between Badminton players with and without unilateral and bilateral lower limb injury history, which could not be assessed using upper trunk-mounted IMUs.

Overall, these findings highlighted the limitations of upper trunk-mounted IMUs for assessing training load in Badminton. By contrast, tibia-mounted IMUs received positive responses from coaches for use during training and provided a novel tool for assessing sport-specific lower limb loading and asymmetries in adolescent Badminton players.

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Chapter 1: Introduction

1.1 Introduction to Load

The term “load” is commonly used to refer to several different mechanisms effecting an athlete during training and competition. A framework for differentiating between types of load, namely physiological load and biomechanical load, was conceptualised by Vanrenterghen *et al.* (2017), where a car analogy was used to explain the difference, see Figure 1. In this car analogy, the physiological adaptations would be the car engine, where the key focus is on the consumption of fuel and oxygen, and the biomechanical adaptations would be the car suspension system, where the key focus is on keeping the mechanical properties intact.

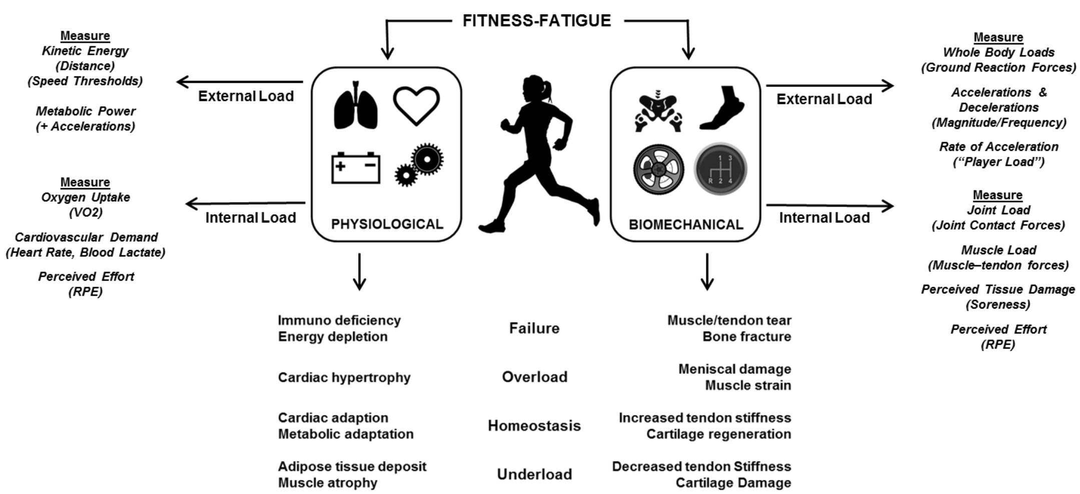
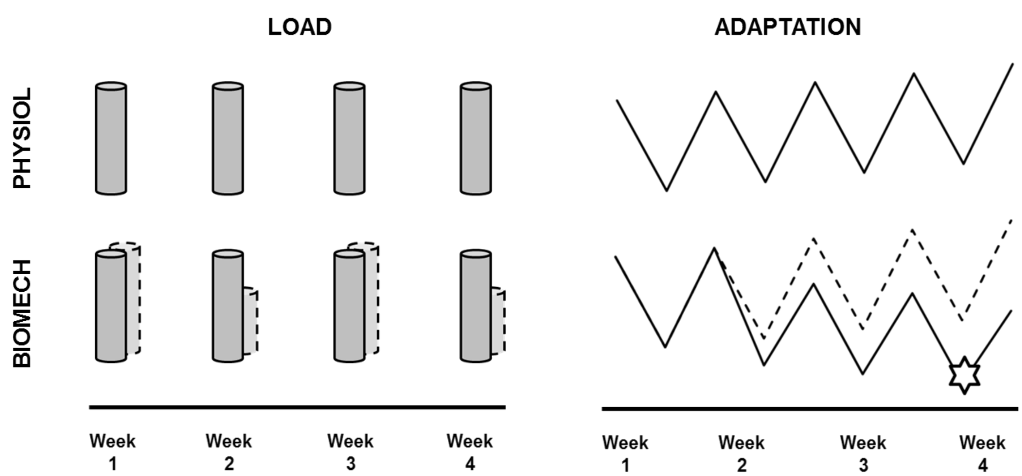


Figure 1 - Player Monitoring Framework for Physiological and Biomechanical Load (Vanrenterghen *et al.*, 2017)

Understanding the difference between physiological and biomechanical load is important as adaptations from these different forms of loading occur at different timeframes. For example, recovery from physiological load may take only a few hours for a well-trained athlete, while recovery from biomechanical load may take a few days. The danger would occur when an athlete returns to full training when recovered from the physiological load but under recovered from the biomechanical load, which may result in overuse injury. Conversely, if an athlete only continues physiological loading when fully recovered from the biomechanical load, the physiological system may be undertrained which would result in a performance decrement. Figure 2 demonstrates a theoretical example of this process (Vanrenterghen *et al.*, 2017). It is therefore essential that practitioners are able to differentiate between the mechanisms of loading when monitoring athletes in training and competition.



* The dotted bars represent an alternative biomechanical load periodisation, leading to an improved biomechanical adaptation profile, as shown by the dotted line. The star indicates a theoretical time point where critical weakness and tissue failure could more likely occur.

Figure 2 - Theoretical Example of Different Time Frames between Physiological and Biomechanical Load (Vanrenterghen *et al.*, 2017)

Monitoring athlete loading, whether in training or competition, is important for determining whether athletes are adapting to their training programme, understanding the need for recovery and reducing injury risks (Bourdon *et al.*, 2017). While the optimal “dose” of load will create adaptations that may result in performance improvement, too little will blunt adaptations and too much may result in overuse injury and illness (Vanrenterghen *et al.*, 2017).

Sudden spikes in load have been demonstrated to be related to injury across a range of sports (Gabbett, 2016) and the management of load in a youth population is especially important as there is a growing body of evidence that has demonstrated an increased risk of overuse injuries amongst youth athletes, with proposed links between inappropriate loads and injury and illness within this population (Murray, 2017). This evidence indicates that when dealing with youth athletes, planning appropriate training loads and management of loading patterns is important to support a long sporting career (Bourdon *et al.*, 2017).

1.1.1 Criticism of “Load”

While the use of terms such as “load”, “workload”, “training load” and “Player Load” are common within both the scientific literature and applied setting, it has been highlighted that these terms may be inappropriate and potentially confusing given the lack of clarity regarding what is being measured (Staunton *et al.*, 2021).

While the terms “work” and “load” have prescribed units of measurement under the Système International d'Unités (SI), being joule (J) and newton (N) respectively, these measures are rarely used when reporting load in a training context. The term “intensity” has been suggested for describing how hard somebody is exercising to avoid misuse of mechanical constructs such as “load” and “work” (Staunton *et al.*, 2021). The term “training magnitude” may also be a more appropriate term, as this would denote the size of the demand being placed on the athlete during training. While the limitations of the term “load” are recognised, the prevalence of use in both the scientific and applied context would make its use unavoidable, and the use of other terms may create further confusion. As such, the term “load”, will be used throughout this thesis, with the method for calculating load being clearly articulated within each study. The clear articulation of how load is being calculated remains an essential step for practitioners to ensure that the construct which is being measured can be clearly understood by the reader.

1.1.2 Measurement of Load

The use of global positioning system (GPS) technology has become increasingly prevalent in elite sport to understand athlete movement and loading. GPS has been used to provide accurate data on the movement of athletes across a range of team sports such as Australian Football, Football (Soccer), Rugby Union, Rugby League, Cricket, Hockey, Lacrosse and Netball (Cummins *et al.*, 2013). The major advantages of GPS monitoring are that the data can be generated in real-time and are more precise than through methods such as video-based time-motion analysis (Carling *et al.*, 2009). In addition, the use of GPS technology removes issues of inter-observer reliability and the subjectivity of classifying athlete movement, for example consistently distinguishing between Striding and Sprinting, which can be difficult to visually assess (Spencer *et al.*, 2004; Wylde *et al.*, 2014). However, the use of GPS has been limited to predominantly field-based team sports as the technology can only be used in an outdoor setting with sufficient satellite coverage (Dellaserra *et al.*, 2014). Several local position systems (LPS) and semi-automated camera solutions are available but at present these are restrictive due to the additional hardware requirements (Gageler *et al.*, 2015) and the prohibitively high cost (Cormack *et al.*, 2013). As a result, there are limitations to the measurement of athlete loading in indoor court-based sports.

To overcome the limitations of GPS, LPS and semi-automated camera solutions, inertial measurement units (IMUs) have become an integral tool for athlete monitoring. IMUs normally comprise three gyroscopes, three accelerometers and magnetometers with changes in orientation calculated based on a combination of these signals (Baca *et al.*, 2009). Training load calculated from the accelerometers housed within IMUs has been used to assess athletes in a variety for indoor court-based sports, such as Badminton (Abdullahi *et al.*, 2019), Basketball (Scanlan *et al.*, 2014), Netball (Cormack *et al.*, 2013) and Tennis (Galé-Ansodi *et al.*, 2017).

IMUs are light, portable, inexpensive, easy to set up, allow for rapid evaluation of a large number of athletes (Picerno *et al.*, 2011) and enable athletes to be monitored in an indoor training environment (Boyd *et al.*, 2011). IMUs also provide the added benefit of allowing athletes to perform normal movements with little encumbrances in their normal training environment rather than in a sport science or biomechanics laboratory (Zak, 2014). However, upper trunk-mounted IMUs have been shown to exhibit poor reliability and were found to be non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). Therefore, the consideration as to whether the upper trunk is the ideal location for IMU placement depends on a critical understanding of what information can be obtained from a specific sensor location.

IMUs worn on the lower limbs have been found to measure forces more directly than units mounted on the upper trunk (Glassbrook *et al.*, 2020b). Lower limb-mounted IMUs have been shown to be suitable for measuring accelerations during sprinting (Glassbrook *et al.*, 2020a), impact loading (Burland *et al.*, 2021) and lower limb asymmetry (Glassbrook *et al.*, 2020b) in field-based sports. In addition, in a study of Cricket fast bowlers, time to peak tibial accelerations during the front foot impact differentiated between athletes with and without lower back pain (Senington *et al.*, 2020).

While the use of IMUs with outdoor team sports has been extensively explored, the use of IMUs within indoor court-based sports requires further investigation to more fully understand the application for training load monitoring, injury management and return to training protocols. To better understand the applications of IMUs in indoor court-based sports, a single sport, namely Badminton, will be studied for the purpose of this thesis.

1.2 Selection of Badminton

Badminton is amongst the most watched and played sports in the world, with approximately 200 million people playing worldwide (Kwan *et al.*, 2010). Badminton has a high prevalence of injury, with an injury incident rate of 3.4 per 1,000 playing hours and significantly higher injury rates in matches (11.6 per 1,000 hours) compared to training (2.08 per 1,000 hours) (Guermont *et al.*, 2021). In elite Badminton players, lower limb injuries have accounted for between 43% (Yung *et al.*, 2007) and 54% (Guermont *et al.*, 2021) of all injuries sustained. Despite the global interest in Badminton, the sport is comparatively under researched (Phomsoupha and Laffaye, 2014). Given Badminton's high prevalence of lower limb injuries, it provides an ideal environment to assess the potential uses of IMUs in an applied setting. Findings from the study of Badminton would likely have implications for other indoor court-based sports.

1.3 Project Aims

The overall aim of this thesis is to provide insight into the use of IMUs for the assessment of training load, measurement of movement asymmetries and use in return to training protocols within a population of Badminton players. Findings from the study of Badminton would be transferrable to a number of other indoor court-based sports. To seek insights regarding the current utilisation of IMUs within Badminton and other court-based sports, a thorough literature review will be conducted. The aim of the literature review is to outline the current knowledge regarding the use of IMUs within court-based sports and to identify potential gaps in understanding which warrant further investigation. Based on the knowledge gaps identified from the literature review a number of research questions will be identified which will be investigated within the thesis.

Chapter 2: Review of Literature

2.1 Purpose of the Literature Review

This review seeks to explore the strengths and limitations of the methods currently being used to analyse athlete movement and training load in indoor court-based sports, with a primary focus on Badminton. For relevant approaches that have not yet been applied directly to indoor court-based sports, examples from other sports will be explored. The review will have a particular focus on the use of IMUs to quantify athlete movement and training load and will aim to provide understanding to the extent to which IMUs are currently being utilised for this purpose. For the purpose of this review, athlete monitoring systems with integrated GPS, accelerometers and gyroscopes will be classified as IMUs provided the GPS function is not the primary source of data used in the particular study. Also, unless otherwise stated, “load” refers to the external training load acting on the athletes (what the athlete is being required to do during training or competition) as oppose to internal load (how the athlete responds to this stimulus).

2.2 Badminton Overview

Badminton is a court-based racket sport that is characterised by periods of high intensity interspersed with short rests (Alcock and Cable, 2009), which requires both aerobic and anaerobic energy systems (Wonisch *et al.*, 2003). An epidemiology study of 266 adolescents reported that of the sports investigated, Badminton was the sport with highest instances of injury, with an injury incident rate of 7.1 per 1,000 of playing hours, compared to Gymnastics (6.8 per 1,000), Rugby Union (6.0 per 1,000 hours), and Basketball (5.6 per 1,000 hours) (Weir and Watson 1996). A more recent study of elite Badminton players found injury incident rates of 3.4 per 1,000 playing hours, with significantly higher injury rates in matches (11.6 per 1,000 hours) compared to training (2.08 per 1,000 hours) (Guermont *et al.*, 2021). In elite Badminton players, lower limb injuries accounted for between 43% (Yung *et al.*, 2007) and 54% (Guermont *et al.*, 2021) of all injuries sustained. Furthermore, 64% of injuries recorded in youth Badminton players were soft-tissue sprains and strains, with knee injuries accounting for 42% of lower limb injuries (Goh *et al.*, 2013).

In addition to lower limb injuries, asymmetries of the lower limb have been reported in Badminton players. Greater width and thickness of the patellar and Achilles tendon in the dominant leg has been identified (Bravo-Sanchez *et al.*, 2019) as has larger dominant leg circumference (Petrinovic *et al.*, 2015). In a study of step forward lunge and jump lunge tasks by Badminton players, it was found that the dominant leg produced greater force across a range of metrics for both movements (Nadzalan *et al.*, 2017). This is a potential area for concern as lower limb asymmetry has been shown to be associated with poorer vertical jump performance and change of direction speed in youth racket sport athletes (Madruga-Parera *et al.*, 2020) as well as being linked to injury risk across a number of sports (Helme *et al.*, 2021).

2.2.1 Temporal Structure

Phomsoupha and Laffaye (2014) conducted a systematic review of the game characteristic, anthropometry, physiology, visual fitness, and biomechanics of Badminton.

In this review a number of studies were shown to have explored the temporal structure of Badminton, including looking at match duration, rally time, effective playing time and work density.

Since the adoption of the new Badminton scoring system in 2006, match durations have been recorded ranging from 2,378.0 (± 387.9) to 1,689.33 (± 312.89) s for senior international male players and at 1,696.1 (± 170.4) s for senior international female players (see Table 1). For national youth level (mean age 15.7 ± 1.2 years) match duration has been recorded as 1036.2 ± 160.2 s for male players and 1028.4 ± 58.2 s for female players (Ming *et al.*, 2008). This highlights the longer match duration and increased load seen at senior international competitions compared to youth level competition.

Table 1 - Comparative Results of Match Duration (Phomsoupha and Laffaye, 2014)

Population	**No of Participants**	**Match Condition**	**Match Duration (s) - Male**	**Match Duration (s) - Female**	**Reference**
Senior International	20	Real Match Play	2,378.0 ± 387.9	1,696.1 ± 170.4	Abian-Vincen *et al.*, 2013
Senior International	40	Real Match Play	Set 1: 1,124.6 ± 229.9 Set 2: 1,260.3 ± 267.1	-	Abián *et al.*, 2014
Senior International	11	Real Match Play	1,689.3 ± 312.9	-	Cabello Manrique *et al.*, 2003
Senior International	16	Simulated Match Play	1,949.7 ± 147.6	-	Chen *et al.*, 2008
Senior International	10	Simulated Match Play	1,740.0 ± 180.0	-	Chen *et al.*, 2011

Senior National	79	Real Match Play	2,090 ± 921	1,638 ± 930	Cabello *et al.*, 2004
Youth National	16	Real Match Play	1,036.2 ± 160.2	1,028.4 ± 58.2	Ming *et al.*, 2004

In studies which recorded rally times, mean rally times were reported ranging from 9.1 (± 1.4) to 5.5 (± 4) s in senior international male players and 8.1 (± 1.7) to 7.8 (± 1.5) s in senior international female players (see Table 2). Senior national level rally times reduce to 7.3 (± 1.3) for male players and 6.3 (± 1.4) for female players (Cabello *et al.*, 2008). For youth level players, rally times decreased further to 4.62 (± 0.86) s for male players and 4.16 (± 0.24) s for female players (Ming *et al.*, 2008). These results reflect a general increase in rally time as the level of competition increases and longer rally time in male matches compared to female matches.

Table 2 - Comparative Results of Rally Time (Phomsoupha and Laffaye, 2014)

Population	**No of Participants**	**Match Condition**	**Rally Time (s) - Male**	**Rally Time (s) - Female**	**Reference**
Senior International	20	Real Match Play	Set 1: 9.0 ± 0.9 Set 2: 9.1 ± 1.4	Set 1: 7.8 ± 1.5 Set 2: 8.1 ± 1.7	Abian-Vincen *et al.*, 2013
Senior International	40	Real Match Play	9.0 ± 1.1 10.4 ± 2.1	-	Abián *et al.*, 2014
Senior International	11	Real Match Play	6.4 ± 1.3	-	Cabello Manrique *et al.*, 2003
Senior International	16	Simulated Match Play	8.2 ± 0.2	-	Chen *et al.*, 2008
Senior International	10	Simulated Match Play	6.0 ± 0.6	-	Chen *et al.*, 2011

Senior International	12	Simulated Match Play	5.5 ± 4.0	-	Faude *et al.*, 2007
Senior National	79	Real Match Play	7.3 ± 1.3	6.3 ± 1.4	Cabello *et al.*, 2004
Youth National	16	Real Match Play	4.6 ± 0.9	4.16 ± 0.2	Ming *et al.*, 2008

Rest time also varied depending on the level and age of the competition. In senior international competitions rest times ranged from 25.2 (± 4.6) to 11.4 (± 6.0) s for male players and 18.2 (± 3.5) to 17.6 (± 2.4) s for female players (see Table 3). At senior national level rest times decreased to 14.2 (± 3.4) s for male players and 13.7 (± 4.2) s for female players, while at youth level rest times dropped further to 9.71 (± 1.32) s for male players and 10.53 (± 0.35) s for female players.

Table 3 - Comparative Results of Rest Time (Phomsoupha and Laffaye, 2014)

Population	**No of Participants**	**Match Condition**	**Rest Time (s) - Male**	**Rest Time (s) - Female**	**Reference**
Senior International	20	Real Match Play	Set 1: 24.1 ± 3.8 Set 2: 25.2 ± 4.6	Set 1: 17.6 ± 2.4 Set 2: 18.2 ± 3.5	Abian-Vincen *et al.*, 2013
Senior International	40	Real Match Play	24.7 ± 4.3 s 26.7 ± 4.6 s	-	Abián *et al.*, 2014
Senior International	11	Real Match Play	12.9 ± 2.7	-	Cabello Manrique *et al.*, 2003
Senior International	12	Simulated Match Play	11.4 ± 6.0	-	Faude *et al.*, 2007
Senior National	79	Real Match Play	14.2 ± 3.4	13.7 ± 4.2	Cabello *et al.*, 2004
Youth National	16	Real Match Play	9.7 ± 1.3	10.5 ± 0.4	Ming *et al.*, 2008

Effective playing time was generally more comparable between senior and youth players, with effective playing times ranging from 36.4 (± 2.4) to 27.3 (± 2.4) % for senior international males and 32.2 (± 3.3) % for national youth male players (see Table 4). Similarly, for female players effective playing times were recorded at 31.4 (± 2.6) to 31.3 (± 2.1) % for senior players and 28.3 (± 0.8) % for youth players.

Table 4 - Comparative Results of Effective Playing Time (Phomsoupha and Laffaye, 2014)

Population	**No of Participants**	**Match Condition**	**Effective Playing Time (%) - Male**	**Effective Playing Time (%) - Female**	**Reference**
Senior International	20	Real Match Play	Set 1: 28.1 ± 3.4 Set 2: 27.3 ± 2.4	Set 1: 31.4 ± 2.6 Set 2: 31.3 ± 2.1	Abian-Vincen *et al.*, 2013
Senior International	40	Real Match Play	27.7 ± 2.9 28.0 ± 2.7	-	Abián *et al.*, 2014
Senior International	10	Simulated Match Play	36.4 ± 2.4	-	Chen *et al.*, 2011
Senior International	12	Simulated Match Play	31.2 ± 2.8	-	Faude *et al.*, 2007
Youth National	16	Real Match Play	32.2 ± 3.3	28.3 ± 0.8	Ming *et al.*, 2008

Work density ratios, being the ratio of physical activity (work) to recovery (rest), were also more comparable between the senior and youth players. Work density ratios for senior international players ranged from 0.57 (± 0.06) to 0.36 (± 0.04) for male players and 0.45 (± 0.05) to 0.44 (± 0.04) for female players (see Table 5). For youth national players, work density ratios were recorded at 0.46 (± 0.07) for male players and 0.40 (± 0.02) for female players.

Table 5 - Comparative Results of Work Density Ratio (Phomsoupha and Laffaye, 2014)

Population	**No of Participants**	**Match Condition**	**Work Density Ratio - Male**	**Work Density Ratio - Female**	**Reference**
Senior International	20	Real Match Play	Set 1: 0.38 ± 0.06 Set 2: 0.36 ± 0.04	Set 1: 0.45 ± 0.05 Set 2: 0.44 ± 0.04	Abian-Vincen *et al.*, 2013
Senior International	40	Real Match Play	0.37 ± 0.05 0.39 ± 0.05	-	Abián *et al.*, 2014
Senior International	11	Real Match Play	0.49 ± 0.06	-	Cabello Manrique *et al.*, 2003
Senior International	10	Simulated Match Play	0.57 ± 0.06	-	Chen *et al.*, 2011
Senior International	12	Simulated Match Play	0.51 ± 0.34	-	Faude *et al.*, 2007
Senior National	79	Real Match Play	0.53 ± 0.12	0.47 ± 0.08	Cabello *et al.*, 2004
Youth National	16	Real Match Play	0.46 ± 0.07	0.40 ± 0.02	Ming *et al.*, 2008

As outlined in a previous review (Phomsoupha and Laffaye, 2014), while there are numerous studies analysing the temporal structure of Badminton, there appears to be an absence of research which quantifies the activity profiles and load of Badminton players in competition or training, especially when compared to other racket sports such as Tennis and Squash (O'Donoghue *et al.*, 2013). The majority of the studies which have sought to assess the load of Badminton have looked at internal load measurements, such as Rate of Perceived Exertion (RPE), heart-rate and blood lactate (Majumdar *et al.*, 1997; Gosh, 2008; Alcock and Cable, 2008; Fernandez-Fernandez, 2013). While there is value in assessing internal load, there are inherent limitations with these approaches.

RPE is the most commonly used method of internal load monitoring as it is inexpensive, easy to administer and requires little or no equipment. However, RPE measures should not be considered in isolation and should be assessed in conjunction with other more objective measures, especially when being used with youth athletes who may not have the ability to accurately self-report (Bourdan *et al.*, 2017). While session RPE has been shown to be a valid form of quantifying training load in youth athletes (Haddad *et al.*, 2011; Padulo *et al.*, 2014), it has been observed that youth athletes with greater training experience are able to more accurately perceive exertion compared to youth athletes with less experience (Barroso *et al.*, 2014). In addition, a study of elite junior Tennis players highlighted the complexity of load perception using RPE (Murphy and Reid, 2013). In this study, the session RPE and drill RPE from junior Tennis players during training were compared to the expected session RPE and drill RPE as rated by their coaches. While there were high levels of agreement between actual and expected drill RPE, there were significant differences between the actual and expected session RPE. This study highlighted that for junior Tennis players the total session RPE is greater than the sum of the RPE of the individual drills.

Heart-rate measures have been commonly used in the analysis of Badminton players, exploring different heart-rate responses for difference stroke types (Ghosh, 2008), differences between singles and doubles players (Alcock and Cable, 2009) and gender differences (Fernandez-Fernandez *et al.*, 2013). However, a key limitation of the use of heart-rate measures are that these can be affected by multiple factors such as dehydration and ambient temperature (Achten and Jeukendrup, 2003), limiting the use as a tool for quantifying training load in an applied setting.

Blood lactate has been used in conjunction with heart-rate to assess physiological responses in Badminton (Ghosh, 2008; Alcock and Cable, 2009; Fernandez-Fernandez *et al.*, 2013). However, blood lactate is difficult to assess outside of highly controlled environments, limiting its use for daily athlete monitoring in Badminton as it is virtually impossible to emulate match-like conditions in a laboratory (Wonisch *et al.*, 2003). Given the potential limitations in the approaches for assessing internal load, methods of assessing the external load of athletes as required to provide a more complete picture of the demands of Badminton and to better inform training design.

2.3 Methods for Assessing Movement in Court-Based Sports

2.3.1 Video-Based Time-Motion Analysis

In video-based time-motion analysis, video of matches or training is observed and athlete movement is subjectively classified into one of a list of pre-defined categories. Such analysis has helped coaches gain an improved understanding of the physical and physiological demands placed on their athletes (O'Donoghue, 2008).

In one of the few studies applying time-motion analysis to Badminton, Liddle *et al.* (1996) attempted to quantify the distance covered by Badminton players in match conditions under the old scoring system. In this study, video of elite male competition was used to assess the distance covered by dividing the court into 0.5 metre segments, see Figure 3.

Based on this method it was estimated that an elite male Badminton player would cover 1.8km in a singles match and 1.1km in a doubles match.

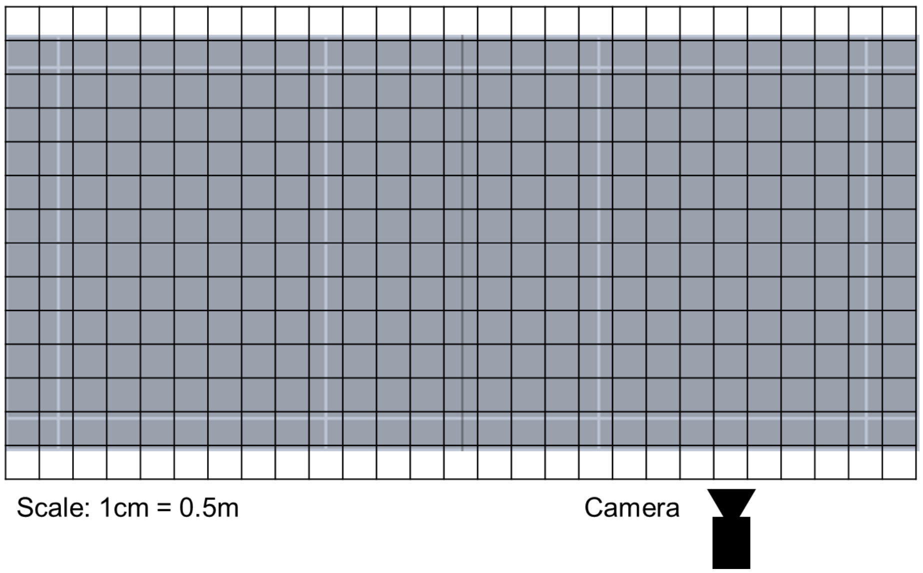


Figure 3 - Diagram of Grid Used to Estimate the Distance Travelled by Players During Elite Male Badminton Competition (Liddle *et al.*, 1996)

Another attempt to use time-motion analysis to quantify Badminton movements was employed by Robinson and O'Donoghue (2008) in the development of a movement classification system to assess agility demands and injury risk across a range of sports. This system was used to describe the player movement in one 39 min men's singles match at a provincial Badminton championship tournament, see Table 6. However, this approach provided only counts and directions of movement and was not able to give information of the intensity, velocity or load associated with the movements.

Table 6 - Frequency of Event Types in a 39 min Men's Singles Match at a Provincial Badminton Championship Tournament (Robinson and O'Donoghue, 2008)

Type of Event	**Left Turn**	**Right Turn**	**No Turn**	**Total**
Smooth	3	0	1	4
Sharp Left	8	9	3	20
Sharp Right	9	16	5	30
Linear	13	12	24	49
Disjointed	62	49	134	245
On The Sport	1	0	0	1
Braking	15	3	44	62
Acceleration	21	22	142	185
Take Off	8	25	44	77
Landing	13	15	47	75

While video-based time-motion analysis is convenient, practical and inexpensive there are issues with the reliability of the data, especially if matches are being notated by different observers (Barris and Button, 2008). In addition, this method of movement analysis is labour intensive (Dobson and Keogh, 2007) and time-consuming. For example, obtaining jump counts for 12 Volleyball players during a two-hour training session using video-based time-motion analysis has been shown to take up to 12 hours to complete (Jarning *et al.*, 2015).

2.3.2 Video Tracking Systems

To overcome the limitations of video-based time-motion analysis, semi-automated video tracking systems have been developed to reduce the time spent to quantify athlete movement. Vuckovic *et al.* (2009) used the SAGIT/Squash tracking system to compare the movement patterns of Squash players from the World Team Championship with players in Slovenian national championships and a local recreational tournament. The system used image-processing techniques to analyse match play filmed by a camera located on the ceiling of the Squash court. The authors found that the best performance indicator was the frequency of occupation of the T area at the moment the opponent was playing their shot. However, a subsequent paper highlighted the limited reliability of the system, due to inherent noise in the software and the effects of body movement of the tracking accuracy (Vuckovic *et al.*, 2010).

Chow *et al.* (2014) used a similar approach as a means of assessing movement in Badminton matches. A 25Hz closed-circuit television (CCTV) system was installed on the ceiling of a multi-purpose hall was used together with the A-Eye motion analysis software (Barris, 2008). In this study positional data was obtained to understand how changing task constraints, between cooperative and competitive, would affect patterns of play. This setup was able to measure distances and angles of the participants while the different stroke types were recorded using two side-on digital video cameras.

While these approaches allow for automated quantification of movement, the major drawback is that only courts with the systems installed can be analysed, meaning that training and competitions at other venues would not be accessible. In addition, the reliability of these systems is subject to issues around noise and player movement (Vuckovic *et al.*, 2010). Given the limitation of these approaches it is necessary to find another method for quantifying movements in Badminton matches. This approach should ideally provide reliable data on playing movement while being portable so it can be used on any training or competition court.

2.3.3 Global Positioning System Technology

Due to the limitations of video-based time-motion analysis and video tracking systems, the use of GPS technology has become increasingly prevalent in elite sport. GPS has been used to provide accurate data on the movement of athletes across a range of team sports such as Australian Rules Football, Football (Soccer), Rugby Union, Rugby League, Cricket, Hockey, Lacrosse and Netball (Cummins *et al.*, 2013). The major advantages that GPS has over video-based time-motion analysis are that the data can be generated in real-time and are more precise (Carling *et al.*, 2009). In addition, the use of GPS technology removes issues of inter-observer reliability and the subjectivity of classifying athlete movement, for example consistently distinguishing between Striding and Sprinting, which can be difficult to visually assess (Spencer *et al.*, 2004; Wylde *et al.*, 2014).

GPS technology has been used to measure distances and classify movement speeds in outdoor racket sports, such as Paddle Tennis (Castillo-Rodríquez *et al.*, 2014). However, while 5Hz GPS units (Catapult Innovations, Melbourne, Australia) have been found to have high reliability for the measurement of distance covered at low and medium speeds, the reliability was found to decrease when actions speeds were higher than 16 km/h (Petersen *et al.*, 2010). As such, GPS technology may be unsuitable for confined movement, court-based sports. Duffield *et al.* (2009) assessed the accuracy and reliability of 5Hz (Catapult Innovations, Melbourne, Australia) and 1Hz (GPSports, Canberra, Australia) units for tracking movement of a Tennis player during a range of sport-specific drills. The data from these units were compared against movement data obtained from high-resolution motion analysis system (Vicon Motion Systems, Oxford, UK) markers which were also worn by the athlete. The results showed that both the 1 and 5 Hz devices recorded significant differences to the high-resolution motion analysis device measurements by underestimating both the distance and speed, with greater differences observed during the faster speed movements.

Low *et al.* (2015) used 5Hz GPS units (Catapult Innovations, Melbourne, Australia) to assess the movement of adolescent Netball players in an outdoor match and compared the results to data from video-based time-motion analysis. Based on this comparison, it was found that the GPS under reported the frequency and duration of high intensity movements and the authors suggested that video-based time-motion analysis was still the preferred method to classify the intensity of movement in Netball. However, it was acknowledged that units with higher sampling rates, 10Hz or 15 Hz, may be more accurate. It has been demonstrated that 10Hz units (Catapult Innovations, Melbourne, Australia) are two to three times more accurate than 5Hz units and provide an acceptable tool for the measurement of constant velocity, acceleration, and deceleration during straight-line running (Varley *et al.*, 2012). Irrespective of the accuracy and reliability of GPS, the use has been limited to predominantly field-based team sports as the technology can only be used in an outdoor setting with sufficient satellite coverage (Dellaserra *et al.*, 2014).

Local positioning systems (LPS) allow for similar metrics to those from GPS to be measured in an indoor environment. Rojas-Valverde *et al.* (2020) utilised a LPS system (RealTrack Systems, Almería, Spain) to assess gender differences in activity profiles of junior international Badminton players. In this study, metrics including distance, acceleration, jumps and take-offs were tracked. It was found that in the male athlete group relative distance, maximum acceleration, relative jumps and average take offs were determinants of performance, whereas for female athletes these determinants were relative distance and maximum acceleration. The main limitations of LPS systems are the additional hardware requirements, such as pre-installed venue infrastructure (Gageler *et al.*, 2015), and the prohibitively high cost (Cormack *et al.*, 2013), which means that it is difficult to use this approach for large scale athlete monitoring.

2.3.4 Accelerometers

The use of accelerometers has provided suitable information for measuring physical activity and a range of human movements (Yang and Hsu, 2010). Accelerometers are sensors which measure the acceleration of an object in motion along reference axes (Yang and Hsu, 2010). Accelerometers were first investigated in the 1950s to measure gait velocity and acceleration (Saunders *et al.*, 1953) with the measurement of human movement being studied in more detail during the 1970s (Morris, 1973). Accelerometers have since been used for a wide range of purposes such as posture and movement classification, estimation of energy expenditure and fall detection and balance control evaluation (Yang and Hsu, 2010).

In 2001, uniaxial accelerometers (Shalimar, Florida, USA) were shown to be a valid method for accessing physical activity intensity in adolescent Basketball players (Coe and Pivarnik, 2001). The data obtained from the uniaxial accelerometers showed a moderate to good correlation with heart-rate data obtained from Polar heart-rate monitors (Polar Electro Oy, Kempele, Finland) and was able to distinguish between the various levels of the Children's Activity Rating Scale (Puhl *et al.*, 1990). However, a limitation with the use of uniaxial accelerometers was that only one plane of movement was measured, possibly leading to the physical activity being underestimated (Montgomery *et al.*, 2010).

The limitations of uniaxial accelerometers have been overcome through the use of the multiple accelerometers. The development of tri-axial accelerometers enables recording of multidirectional body movement, thereby improving the energy expenditure estimations (Krasnoff *et al.*, 2008). Tri-axial accelerometers have been used in a number of settings to assess movement of both athletic and general populations. In a clinical setting these have included the mounting of a tri-axial accelerometer on the upper and/or lower back to assess relative motion of different segments of the thoracolumbar spine (Alghtani *et al.*, 2015b), the relationship between the kinematic profiles of flexion of the upper lumbar and lower lumbar (Alghtani *et al.*, 2015a), range of motion of the lumbar spine (Alghtani *et al.*, 2016) and hop landing balance (Williams *et al.*, 2019). However, tri-axial accelerometers are still susceptible to issues pertaining to signal noise and errors around gravity which may prove problematic when used in a court-based setting (Baca *et al.*, 2009).

2.4 Inertial Measurement Units

IMUs have been used to obtain reliable data that will account for the issues of noise and gravity. IMUs normally comprise three gyroscopes, three accelerometers and magnetometers with changes in orientation calculated based on a combination of these signals (Baca *et al.*, 2009). IMUs are light, portable, inexpensive, easy to set up and allows for rapid evaluation of a large number of athletes (Picerno *et al.*, 2011). The use of IMUs avoids many of the limitations of video-based time-motion analysis and GPS such as reduced labour compared to time-motion analysis, a higher sampling rate than GPS and the ability for athletes to be monitored in an indoor training environment (Boyd *et al.*, 2011). IMUs also provided the added benefit of allowing the athletes to perform normal movements with little encumbrances in their normal training environment rather than in a sport science or biomechanics laboratory (Zak, 2014).

2.4.1 Reliability of IMUs

A number of studies have sought to evaluate the reliability of IMUs to assess athlete movement. Boyd *et al.* (2011) assessed the reliability of the IMUs within the MinimaxX GPS units (Catapult Innovations, Melbourne, Australia) in both a laboratory setting and field setting with Australian Rules Football players. For the laboratory setting, eight IMUs were attached to a hydraulic universal testing machine (Instron 8501) and oscillated over two protocols (0.5 g and 3.0 g) to assess intra- and inter-unit reliability. For the field setting, IMU data was collected over nine Victorian Football league matches, where each of the 10 players wore two units at the upper trunk which were taped together so that the axes were aligned. It was found that in both the laboratory and field assessments the IMUs demonstrated an acceptable level of technical reliability, with coefficient of variation (CV%) score of between 0.91% and 1.10% in the laboratory assessment and 1.96% in the field assessment. This highlighted that the IMUs could be confidently applied to assess changes over multiple periods of activity or between players and were suitable for detecting differences in Australian Rules Football physical activity.

Hurst *et al.* (2014) highlighted the potential for IMUs to be used to assess workload demands in combat sports, such as Mixed Martial Arts (MMA), and sought to determine the reliability of IMUs for measuring the workload of MMA specific movements. Eight MMA exponents each wore an IMU (Catapult Innovations, Melbourne, Australia) positioned at the upper trunk, between the scapulae, and were required to perform a series of isolated strikes and ground movements. It was found that the IMUs generally had high intra- and inter-unit reliability (with intra-class correlations of >0.8 and *p*-values of <0.001). The exceptions were a few movements (knee strike and offensive takedown) where the inter-unit reliability was moderate. The authors also discussed the use of data obtained from IMUs in assessing an athlete's technique in performing an individual movement. They suggested that high variability in the data recorded from the IMUs may suggest inconsistency in the athlete's technique, fatigue or progressive movement learning. This information could be used to determine benchmark values for athletes of different abilities or weight categories.

Van Iterson *et al.* (2017) used the test-retest method to assess the reliability of Optimeye S5 units (Catapult Innovations, Melbourne, Australia) to measure Ice Hockey specific movements, which were then used to calculate the training load. A group of collegiate Ice Hockey players completed nine ordered tasks in a single bout. These tasks were then repeated in the same order during a second bout. The comparison of the training load data derived from the IMU indicated that the training load values were distinctly different between the nine Ice Hockey tasks and large to perfect test-retest reliability was observed in eight of the nine tasks, with intra-class correlation coefficients (ICC) ranging from 0.68 to 0.98.

The Otimeye S5 units were also found to be reliable for use for Handball specific movements (Luteberget *et al.*, 2018). A group of 10 Handball players (5 male and 5 female) each wore two units aligned to the accelerometer and gyroscope axes at the upper trunk in the purpose-built harness. In a laboratory-based assessment each participant completed seven movement tasks, including various change of direction and start/stop actions. In addition, the participants also wore the IMUs during 12 handball training sessions, which were performed as planned by the coach. The IMUs demonstrated good reliability in both the laboratory tests (CV% ranging from 3.1% to 6.7%) and field-based assessment (CV% from 0.4% to 5.6%). The authors concluded that the Otimeye S5 units were able to detect the "real" differences in Handball and could be applied to similar court-based team sports.

2.4.2 IMU Placement

The two most common placements of IMU for activity tracking are at the upper trunk, between the scapulae (Fish and Grieg, 2014; Gageler *et al.*, 2015), and at the hip or lower trunk (Dieu *et al.*, 2014; Jarning *et al.*, 2015). The former is due to many of the athlete monitoring systems positioning the unit between the scapulae in a purpose-built harness to protect the unit from damage, minimise the potential for injury and reduce any restrictions on athlete movement. The latter is based on the assumption that placing the unit nearer to the centre of mass would provide a better estimation of the total body load (Simons and Bradshaw, 2016). This assumption was tested in a study of Gymnastics landings where two IMUs (MinimaxX, Catapult Innovations, Melbourne, Australia) were used, one at the upper trunk and one at the lower trunk (see Figure 4).

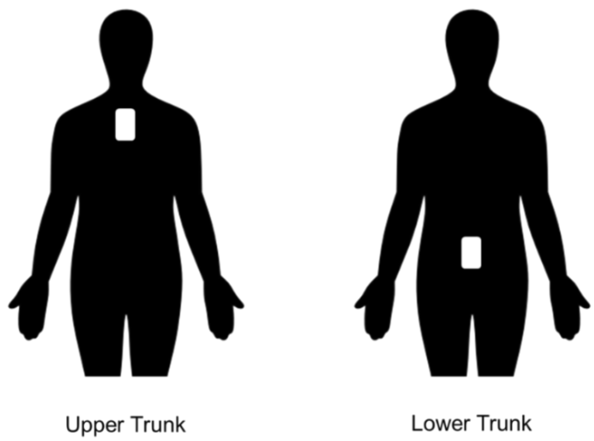


Figure 4 – IMU Placement at the Upper and Lower Trunk (Simons and Bradshaw, 2016)

The 12 female participants were asked to perform two tasks, 10 continuous double leg hops and drop landings with rebound jumps from three box heights (37.5, 57.5 and 77.5cm) on to a single uniaxial force platform (Quattro 9290AD, Kistler Group, Winterthur, Switzerland). Contrary to the initial assumption, the IMU placed at the upper trunk was better able to discriminate between the various heights during drop landings, compared to the IMU placed at the lower trunk. Correlations between ground reaction force and peak resultant acceleration were highest in the hopping task when the IMU was placed at the upper trunk using a 20 Hz filter ($r_s = 0.825$) compared to the lower trunk ($r_s = 0.769$). For the rebound jump task, significant correlations were only found at the 37.5cm drop height for the lower trunk-mounted IMU, whereas significant correlations were observed for all three drop heights when the IMU was placed at the upper trunk. An explanation given in the study attributed these findings to greater soft tissue movement at the lower trunk in comparison to the upper trunk. The results from this study suggest that placement of an IMU at the upper trunk is not only more practical but also provides a closer estimate of total body load.

2.4.3 Limitations of Upper Trunk Mounted IMUs

While upper and lower trunk IMU placement are the most common for many team and individual sports, concerns have been raised regarding the ability to accurately measure athlete loading, especially in the lower limbs. In a study of 10 University Rugby Union players (Edwards *et al.*, 2018), the participants were assessed performing five left and five right running trials across two force platforms (Type 9281CA and 9821EA, Kistler, Winterthur, Switzerland) at three different speeds (slow, medium, fast). The participants were assigned one (n = 4) or two (n = 6) IMUs (GPSports Pty. Ltd., Canberra, Australia) worn at the upper trunk, between the scapulae in a purpose build harness, two wireless Trigno electromyography devices (Delsys, Natick, MA, USA) and markers for a 3D motion capture system (Qualisys AB, Gothenburg, Sweden). The comparison of data from the multiple devices found that upper trunk-mounted IMUs exhibit poor reliability and were found to be non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running. The authors suggested that the elasticised harness of the IMU was one of the major contributors to extraneous accelerometer magnitudes. The high degree of error may also be due to the IMU being positioned far from the point of ground contact, therefore mechanical energy is absorbed and dissipated through the joints and body tissues between the foot and the IMU (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b).

2.4.4 Lower Limb Mounting

While limitations with the trunk-mounted IMUs have been highlighted, lower limb-mounted IMU have been found to provide a more direct measure of lower limb load and ground reaction forces. Having initially been used for analysis of walking gait, tibia-mounted IMUs were found to provide a valuable means of performing running analysis (Kawabata *et al.*, 2013). The advantage of using tibia mounted IMUs is the relatively small amount of soft tissue present between the skin and bone which minimises loss of accuracy observed in trunk-mounted IMUs (Lucas-Cuevas *et al.*, 2017). In a study of 30 male runners, Lucas-Cuevas *et al.* (2017) attached three IMUs on the forehead, distal tibia and proximal tibia and instructed participants to perform three 2-minute runs at various speeds on a treadmill. It was found that placing the IMU at the proximal tibia resulted in lower magnitudes compared to placement at the distal tibia. This highlighted the need for consistent placement of the IMU for use in the analysis of lower limb loading.

In a study of 16 recreational athletes, participants were required to wear four IMUs (iMeasureU, Auckland, New Zealand) on the left and right tibia and on the laces the left and right shoes (Glassbrook *et al.*, 2020a). Participants were then asked to run at various speeds (from 60% to 100% of max effort) for durations of 15 and 60 sec. It was found that acceleration patterns were similar for the tibia and shoe mounted IMUs but that resultant accelerations tended to be greater when measured at the shoe, again highlighting the importance of task dependant IMU placement and the need for consistent placement between trials during athlete monitoring.

Outside of running analysis, lower limb-mounted IMUs have been used in field-based team sports. In a study of 10 recreational Football (Soccer) players, participants were required to wear two IMUs (IMeasureU, Auckland, New Zealand) on the left and right tibia and were asked to perform three trials of four tasks: acceleration-deceleration, plant and cut, change of direction and ball kick (Burland *et al.*, 2021). Cumulative impact load and number of steps taken were recorded during the four tasks. In this context, impact load is calculated by multiplying the number of steps by the intensity (tibial acceleration value) at which they are taken (Equation 1).

$$Impact\ Load\ =\ \left(\sum 1g\ steps\ \times 1g\right)\ +\ \left(\sum 2g\ steps\ \times\ 2g\right)\ +\ \ldots$$

Equation 1 – Impact Load Calculation (Burland *et al.*, 2021)

It was found that tibia mounted IMUs provided good to excellent reliability for measurement of impact loading and step count for the acceleration-deceleration (ICC range 0.73 to 0.89), plant and cut (ICC range 0.70 to 0.87) and change of direction tasks (ICC range 0.73 to 0.96), but not for the ball kicking task (ICC range 0.58 to 0.87), as the contact with the ball introduced more variability and therefore reduced reliability. Overall this study found tibia-mounted IMUs to be reliable for assessing impact loads in Football (Soccer) specific movement tasks.

In a study of 35 county-level Cricket fast bowlers, data obtained from both trunk-mounted and lower limb-mounted IMUs (THETAmetrix, Portsmouth, UK) were compared against force-plate (Kistler Group, Winterthur, Switzerland) and high-resolution motion analysis system (Vicon Motion Systems, Oxford, UK) data. It was found that the IMUs offer moderate to excellent estimates of reliability (ICC range for tibia acceleration 0.73 to 0.96; ICC range for lumbar kinematics 0.64 to 0.93) and validity (ICC range compared to force-plate 0.64 to 0.98; ICC range compared to motion analysis system 0.61 to 0.99) when used for collecting spinal kinematics and tibial impacts (Senington *et al.*, 2021). This study concluded that IMUs in Cricket fast bowling analysis may offer a cheaper and portable alternative to current, more expensive systems.

2.4.5 IMU Placement in Racket Sports

Specifically, to court-based racket sports, IMUs have been utilised to quantify both lower body and upper body movements and assess forces and loads during training and competition. This has included the concurrent use of multiple IMUs and positioning of the IMUs at the wrist, ankle, lower leg, lower arm, upper arm, racket handle, racket head, upper back and lower back (see Table 7).

Table 7 - Placement of IMU in Racket Sports

Sport	Wrist	Lower Leg	Hand	Lower Arm	Upper Arm	Racket Handle	Racket Head	Upper Back	Lower Back	Reference
Badminton								*		Abdullahi *et al.*, 2019
Badminton							*			Anik *et al.*, 2016
Badminton							*			Chang *et al.*, 2009
Badminton			*	*	*	*				Chew, Su *et al.*, 2015
Badminton	*				*					Chew, Sim *et al.*, 2015
Badminton									*	Dieu *et al.*, 2014
Badminton				*						Jacob *et al.*, 2016
Badminton							*			Koon *et al.*, 2005
Badminton				*						Raina *et al.*, 2017
Badminton	*		*	*	*					Rusydi *et al.*, 2015
Badminton								*		Sasaki *et al.*, 2018
Badminton	*				*	*				Steels *et al.*, 2020
Badminton	*									Taha *et al.*, 2016
Badminton	*	*								Wang *et al.*, 2016
Badminton						*				Yu and Zhao, 2013
Table Tennis	*	*	*	*						Bańkosz & Winiarski, 2020
Table Tennis						*				Blank *et al.*, 2015
Table Tennis						*				Boyer *et al.*, 2013
Table Tennis	*									Guo *et al.*, 2010
Tennis	*				*					Ahmadi *et al.*, 2009
Tennis				*						Connaghan *et al.*, 2011

Tennis		*	Gale-Ansodi *et al.*, 2017
Tennis	*		Kos *et al.*, 2016
Tennis	*		Whiteside *et al.*, 2017
Tennis & Badminton	*		Anand et al 2017

Whilst sensor placement will be important and related to the area under investigation, the use of multiple IMUs could allow for some redundancy in the data collection. However, a potential limitation to the concurrent use of multiple IMUs is that coaches may be reluctant to allow their athletes to wear multiple IMUs during training and competition. While this is an under researched area, an interview study of 113 coaches from 46 athletic-based locations involved in collegiate and professional sports regarding the use of wearable technologies, found concerns expressed regarding the potential inconvenience to the athlete, lack of comfort and appearance and that coaches were reluctant to push their athletes to use these technologies, particularly as athletes may blame the technology for a poor performance (Luczak *et al.*, 2020).

2.5 Application of Inertial Measurement Units

The use of IMUs within indoor court-based sports can be classified into three main categories; (1) to assess the physical demand (load) being placed on an athlete during training and/or competition, (2) to classify the types of movement being performed by the athlete and (3) to assess rehabilitation after injury.

2.5.1 Training Load Monitoring

Monitoring the workload of athletes during training or competition is important for determining whether athletes are adapting to a training programme, understanding the need for recovery, and attempting to reduce injury risks (Bourdon *et al.*, 2017). As the majority of the commercially available athlete monitoring systems contain IMUs (Chambers *et al.*, 2015), the most common use of IMUs within indoor court-based sports has been to assess training load (see Table 8).

Table 8 - Training Load Studies of Court-Based Sports Utilising IMU Measures

Sport	**Placement**	**Measures**	**Finding**	**Reference**
Badminton	Lower Back	Modified Vector Magnitude	Increases in physical activity (non-significant) based on expertise (conative stage). In future research IMUs could be used to assess player's positioning in space and time management during play.	Dieu *et al.*, 2014
Badminton	Upper Back	Player Load compared to heart-rate measures	Player Load and relative distance were both only correlated to the heart-rate measures at the High Intensity zone but not at the Low or Medium Intensity zones, with the latter showing a negative correlation in both cases. High Intensity movements in Badminton, for example an Overhead Smash, would elicit a clear heart-rate response, 183.5 ± 5 bpm (Ghosh, 2008), the overall high work density observed in Badminton compared to field based sports make it difficult to observe clear differences in the Low and Medium Intensity zones.	Abdullahi *et al.*, 2019
Basketball	Upper Trunk	Player Load	Trivial differences (effect size <0.2) between the validation trial, defence and offense drills for the majority of variables.	Montgomery *et al.*, 2010

			IMUs permitted more systematic monitoring of the physical and physiological demands of Basketball training and competition.	
Basketball	Upper Trunk	Player Load compared to RPE, Training Impulse (TRIMP) and Summated-Heart-Rate-Zones (SHRZ)	Significant correlations were observed between the internal and external training load models. Accelerometer derived training load model was the most practical approach to monitor external training load in court-based team sports.	Scanlan *et al.*, 2014
Netball	Upper Trunk	Player Load	Player Load obtained from the IMUs could consistently differentiate between higher and lower standard Netball match play. Higher load performed by Centre court players provided further support for the value for IMUs as a tool for monitoring activity profiles in Netball competition. IMUs provided an innovative and useful tool for assessing activity profiles in Netball and other court-based sports.	Cormack *et al.*, 2013
Netball	Upper Trunk	Player Load compared to heart-rate and RPE	Skills training most closely replicated the movement seen in match play with similar results for Player Load, Forward, Sideways and Vertical movement, but had significantly lower results for heart-rate.	Chandler *et al.*, 2014

			Game-based training and traditional conditioning both produced similar mean heart-rate and peak heart-rate results compared to match play but created a higher Player Load. No difference between match play and the various training methods for RPE despite the different physical activity profiles, suggesting that this method is insensitive when compared to the accelerometer derived training load.	
Netball	Upper Trunk	Player Load	IMUs were able to differentiate between playing position during Netball match-play and was consistent with previously reported notational analysis. Further investigation into injury risk could be conducted by changing the location of the IMU to give site-specific data. IMUs provided an appropriate means to quantify mechanical load in Netball.	Fish and Grieg, 2014

The most common measure in these studies is the parameter called "Player Load", developed by Catapult Innovations (Melbourne, Australia), by integrating data from all three accelerometers within the MinimaxX units (Boyd *et al.*, 2011). This Player Load calculation shown in Equation 2:

$$Player\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2 + (ay_1 - ay_{-1})^2 + (az_1 - az_{-1})^2}{100}}$$

Equation 2: Player Load Calculation (Boyd *et al.*, 2011)

where *ax, ay* and *az* are the orthogonal components of acceleration measured from the tri-axial accelerometer directions at 100 Hz (Boyd *et al.*, 2011).

Based on the analysis of these studies a number of common themes emerged regarding the application of IMUs for training load monitoring in court-based sports: (1) correlation with internal training load, (2) differentiation based on playing standard/experience and (3) differentiation of training/drill type.

2.5.1.1 Correlation with Internal Training Load Measures

A number of the studies examined sought to compare external training load derived from IMUs with internal training load measures, either heart-rate or RPE (Chandler *et al.*, 2014; Scanlan *et al.*, 2014; Abdullahi *et al.*, 2019). In a study of Netball, it was highlighted that while significant differences were observed in external training load and heart-rate measures for the different types of training (skills training, game-based training, traditional training and repeat high-intensity effort training) these differences were not reflected in the RPE scores, highlighting the limitation of this approach when used in isolation (Chandler *et al.*, 2014). In Basketball, the comparison between training load and RPE (Foster *et al.*, 2001), Training Impulse (TRIMP) (Bannister, 1991) and Summated-Heart-Rate-Zones (SHRZ) (Edwards, 1993) found significant correlations between the internal and external measures providing support for commonality between the various approaches (Scanlan *et al.*, 2014).

In Badminton, external training load only correlated to the heart-rate measures at the High Intensity zone but not at the Low or Medium Intensity zones, with the latter showing a negative correlation. The commonality between the external and internal training load measures is due to the internal training load (response) being a product of the external training load (dose), a relationship that had previously been demonstrated in field-based sports (Scott *et al.*, 2013). However, the “response-dose relationship” may not be as strong in court-based sports as in field-based sports, and coaches and practitioners must be mindful when applying findings from field-based team sports to court-based sports (Scanlan *et al.*, 2014). These studies highlight the need for further investigation into external load in court-based sports, as using internal loading measures alone may provide an incomplete picture of the demands being placed on an athlete.

2.5.1.2 Differentiation Based on Playing Standard/Experience

A second common use of IMUs in court-based sports has been to differentiate between players of various playing standards and/or experience (Cormack *et al.*, 2013; Dieu *et al.*, 2014). In the study of Netball, it was found that IMU data could consistently differentiate between higher (Victorian State League Championship) and lower (recreational B grade competition) standard Netball match play (Cormack *et al.*, 2013). This study, as well as others of Netball (Fish and Grieg, 2014), have also demonstrated the ability of data from IMUs to differentiate training load based on playing position. While difference in training load based on playing level were also found in the study of Badminton, these were non-significant (Dieu *et al.*, 2014). The authors of the latter study suggested that Badminton players' physical activity was not significantly associated with their expertise as the players at different expertise stages "differed in intent". This conclusion seems difficult to substantiate as a player's "intent" is dictated, at least in part, by their physical ability, making it problematic to make a clear distinction between the two. The findings from these studies point to the potential use of IMUs to understand the differences between playing standards and enable the design of training programmes to facilitate the transition from one playing level to another, and potentially managing this on a position specific basis for court-based team sports.

2.5.1.3 Differentiation Based on Training/Drill Type

The final common use of IMUs for training load monitoring is for the differentiation of training type and/or training drills (Montgomery *et al.*, 2010; Chandler *et al.*, 2014). In the Basketball study, training load was used to quantify the physical demands of selected offensive and defensive Basketball drills, reduced court area competition and live match play (Montgomery *et al.*, 2010). When normalised for time there were only trivial differences (Effect Size <0.2) between the validation trial, defence and offense drills for the majority of variables. It was found that the physical demand of live match play was substantially more challenging than any of the drills. In Netball, it was found that while game-based training and traditional conditioning both produced similar heart-rate responses to match play, the training load values were significantly higher (Chandler *et al.*, 2014). By contrast, skills training produced similar training load values but lower heart-rate responses. These studies demonstrate how IMUs can be used to quantify different types of training in court-based sports, which enable coaches to build training programmes which meet the specific match demands. This is especially valuable as RPE has been found to unreliable when making these distinctions in court-based sports (Murphy and Reid, 2013; Chandler *et al.*, 2014).

2.5.2 Movement Classification

The use of IMUs for movement classification can be broadly split into two different approaches (1) using a single trunk-mounted IMU and (2) using multiple IMUs to provide a more direct measure of the movement under consideration (see Table 9).

Table 9 - Studies using IMU Data for Movement Classification of Court-Based Sport

Sport	**Placement**	**Measures**	**Finding**	**Reference**
Badminton	Racket Face	Acceleration and Angular Velocity	An IMU placed on the racket face was able to classify fives types of Badminton stroke	Anik *et al.*, 2016
Badminton	Dominant Forearm, Non-Dominant Forearm and Dominant Tibia	Acceleration	Able to recognise 14 Badminton strokes and 5 non-stroke motions	Wang *et al.*, 2013
Badminton	Racket Handle, Dominant Wrist and Dominant Forearm	Acceleration and Angular Velocity	Able to recognise seven Badminton specific movements	Steels *et al.*, 2020
Table Tennis	Paddle	Acceleration and Angular Velocity	An IMU placed with the racket handle was able to classify eight types of forehand and backhand Table Tennis shots.	Blank *et al.*, 2015
Tennis	Chest and Arm	Comparison of accelerations with high resolution motion analysis system (Vicon Motion Systems, Oxford, UK)	While a significant correlation was found between the IMUs and marker-based data, this was only for slow-motion serves. The IMUs used in this study were unable to detect the rate of rotational motions seen in normal speed serves.	Ahmadi *et al.*, 2009
Tennis	Dominant Forearm	Acceleration	The tennis stroke detection system used IMU data to detect tennis stroke type (serve, forehand or	Connaghan *et al.*, 2011

			backhand) of 4 unseen players with 90% accuracy.	
Volleyball	Upper Trunk	Jump Frequency, Jump Height and Time of Flight	Agreement between IMU data and video recording for 95% of the jumps (97% male and 92% female). Margin of error of 0.015 ± 0.06m for jump height between IMU and force plate data.	Gageler *et al.*, 2015
Volleyball	Lower Trunk	Peak Vertical Acceleration (PVA) and Peak Resultant Acceleration (PRA)	Not all PVA or PRA from jumping activities were significantly different from those from non-jumping activities. Large variation of peak vertical acceleration between subjects. The use of peak vertical acceleration data may not be suitable to quantify movements in volleyball	Jarning *et al.*, 2015

2.5.2.1 Single IMU Movement Classification

In the two studies of Volleyball, a single trunk-mounted IMU was used, placed either at the upper or lower trunk (Gageler *et al.*, 2015; Jarning *et al.*, 2015). The first of these studies sought to validate an automatic jump detection method by comparing the IMU data to a video recording and to determine and validate time of flight and estimate jump height by comparing the IMU data to data obtained from a force plate. The comparison of the IMU data with jumps recorded on video found that 95% of the jumps were correctly identified (97% male and 92% female). However, the comparison of jump height between the IMU data and force plate data found a margin of error of 1.5 ± 6.0 cm (Gageler *et al.*, 2015).

The second study sought to distinguish between jumping activities (jump-float serve, block jumping, jump serve and spike jumping) and non-jumping activities (4.5-m side-to-side shuffle steps, 9-m shuttle run and 9-m sprint ending with a floor dive). The authors found that not all the peak vertical acceleration (PVA) or peak resultant acceleration (PRA) from jumping activities were significantly different from those from non-jumping activities. For example, the PVA and PRA values for floor dive were higher than those recorded for jump-float serve, block jump or jump serve. They also found the variation of peak vertical acceleration between subjects was large. These results suggest that the use of peak vertical acceleration data may not be suitable to quantify movements in Volleyball.

A major limitation of this approach was that only the vertical acceleration was analysed as the IMUs used did not contain a gyroscope. Including acceleration data from the other axis and angular velocity data from the gyroscope could make distinguishing between the jumping and non-jumping activities more feasible. For example, a study of Cricket fast bowling used a single IMU placed at the upper trunk, between the scapula to successfully differentiate between bowling and non-bowling movements (99% in training and 95% in competition) (McNamara *et al.*, 2015). A number of data points were used to differentiate between bowling and non-bowling movements, including the back-foot contact from the accelerometers and “roll like” rotation from the gyroscopes. A similar approach within studies of court-based sports may have provided greater insights and improved movement classification.

2.5.2.2 Multiple IMU Movement Classification

A number of studies of court-based sports have used multiple IMUs to classify movements, either on the athlete’s body (Ahmadi *et al.*, 2009; Connaghan *et al.*, 2011; Wang *et al.*, 2013; Steels *et al.*, 2020) or directly on the racket (Blank *et al.*, 2015; Anik *et al.*, 2016; Steels *et al.*, 2020). Studies of Badminton and Tennis placed IMUs on the athlete’s arm, trunk and/or lower limbs to classify movement. In the studies of Tennis mixed results were found, with one study achieving 90% accuracy for the detection of stroke type using IMUs placed on the dominant arm (Connaghan *et al.*, 2011). However, a separate study using IMUs placed on the chest and dominate arm found that movement classification was only possible for slow-motion serves as the IMUs were unable to detect the rate of rotational motions seen in normal speed serves. In the study of Badminton, a combination of three IMUs placed on the dominate forearm, non-dominant forearm and dominant tibia were able to recognise 14 Badminton strokes and five non-stroke motions (Wang *et al.*, 2013).

In addition to placement of IMUs on the athlete's body, IMU placed on the racket have been used to assess stroke type. In a study of 10 Table Tennis players, an IMU placed with the racket handle was able to classify eight types of forehand and backhand Table Tennis shots (Blank *et al.*, 2015), while in a study of Badminton an IMU placed on the racket face was able to classify fives types of Badminton stroke (Anik *et al.*, 2016). Finally, the use of IMUs located on the racket handle, dominant wrist and dominant forearm was able to identify seven Badminton specific movements, with 99% accuracy when data from both the accelerometer and gyroscope were combined (Steels *et al.*, 2020).

The key limitations with the use of IMUs for movement classifications in racket sports is that the IMUs are commonly placed on the dominant limbs (upper arm or forearm) or within the racket, both of which may create interference to the player's technique. As coaches are reluctant for their athletes to wear IMUs due to a perceived lack of comfort and concerns that the athlete will attribute poor performance to the technology (Luczak *et al.*, 2020), the use of multiple IMUs placed on the upper limbs or racket will likely impact the uptake for regular athlete monitoring.

2.5.3 Injury Management

In addition to training load monitoring and movement classification, IMUs have been used to assess injury risk in athlete populations. For example, in a study of a drop jump task, an IMU based system demonstrated good concurrent validity with measurements from a marker-based system and was able to detect movements that were of higher risk of ACL injury (Dowling *et al.* 2011). The authors concluded that wearable IMUs could provide a simple and cost-effective tool for conducting risk screening or for providing focused feedback on injury risk.

In a study of Cricket fast bowlers (14 senior and 21 junior), participants wore three IMUs (3AMG sensors, THETAmetrix, Portsmouth, UK) mounted over T1, L1 and S1 spinous processes and one IMU on each tibia (Senington *et al.*, 2020). For data capture, participants bowled six balls with maximum effort. It was found that in the senior athlete group, time to peak tibial accelerations during the front foot impact differentiated between bowlers with and without lower back pain. For the junior athlete group, medio-lateral sacral acceleration differentiated between bowlers with and without lower back pain. For both groups, bowlers without a history of lower back pain used greater thoracic rotation away from the direction of the delivery, while senior bowlers who demonstrated greater thoracolumbar and lumbar extension either had a history of lower back pain or went on to develop lower back pain. The authors concluded that this provided a suitable method of monitoring bowling biomechanics in Cricket bowlers.

Shoe mounted IMUs (iMeasureU, Auckland, New Zealand) have been used to assess lower limb asymmetry in professional Rugby League players during 8-minute match simulations over 13 testing sessions (Glassbrook *et al.*, 2020b). It was found that the lower limb-mounted IMUs were able to detect clinically meaningful asymmetries (>10%) during high intensity activities (characterised as above 16g) and differences across players. The authors highlighted that an understanding of the nature of the lower-limb accelerations experienced during match-play, coupled with the knowledge of when injury is most likely to occur, may assist in injury prevention strategies.

The use of IMUs to assess lower limb asymmetries is of interest as such asymmetries have been linked to injury risks across a number of sports. The presence of asymmetry between the lower limbs is associated with poorer jump performance, change of direction speed and agility as well as being linked to injury risk (Hoffman *et al.*, 2007; Bell *et al.*, 2014; Steild-Muller *et al.*, 2018; Madruga-Parera *et al.*, 2020; Helme *et al.*, 2021). Within sport medicine, the limb symmetry index is frequently used as a metric to assess the function of the lower limb and track the progression of rehabilitation post injury (Engalen-van Melick *et al.*, 2013; Abrams *et al.*, 2014; Almangoush and Herrington, 2014). The value of <10% limb asymmetry is particularly common as a return to sport criterion (Schmitt *et al.*, 2012; Abrams *et al.*, 2014) and has been used for strength (Brown *et al.*, 2020) and functional performance testing such as hopping distance (Almangoush and Herrington, 2014).

In racket sports lower limb asymmetries have commonly been assessed through specific tests, such as single leg counter movement jumps, single leg broad jumps and change of direction assessments (Table 10). However, these tests may not represent the ability of the athlete to perform the sport specific tasks and may mask underlying deficits in limb function which only become apparent during more sport specific movements. The use of lower limb-mounted IMUs therefore has the potential to provide a means to assess lower limb asymmetries during sport specific tasks, facilitating the management of injury risk and enhancing the return to training process post injury.

Table 10 - Assessment of Lower Limb Asymmetry in Racket Sports

Sport	**Measures**	**Asymmetry % (SD)**	**Reference**
Badminton	SFL		Nadzalan *et al.*, 2017
	- Absolute Peak Concentric Force	4.02	
	- Relative Peak Concentric Force	4.59	
	- Absolute Mean Concentric Force	3.79	
	- Relative Mean Concentric Force	4.17	
	- Absolute Mean Eccentric Force	4.54	
	- Relative Mean Eccentric Force	3.85	
	- Absolute Impact Force	3.71	
	- Relative Impact Force	3.60	
	-Time to Peak Force	-6.98	
	- Stance Time	-2.15	
	JFL		
	- Absolute Peak Concentric Force	6.07	
	- Relative Peak Concentric Force	6.41	
	- Absolute Mean Concentric Force	3.62	
	- Relative Mean Concentric Force	3.55	
	- Absolute Mean Eccentric Force	4.23	
	- Relative Mean Eccentric Force	3.97	
	- Absolute Impact Force	3.59	
	- Relative Impact Force	3.89%	
	-Time to Peak Force	-7.84%	
	- Stance Time	-2.88%	
Badminton	SEBT – Anterior	2.07	Manolova *et al.*, 2018
	SEBT – Posteromedial	-0.14	
	SEBT – Posterolateral	-3.00	
Badminton	SLCMJ		*Yeung et al.,* 2021
	- Control Warm Up	12.98 (7.66)	
	- Loaded Warm Up	9.96 (7.75)	
Tennis	SLCMJ	15.03 (6.91)	Madruga-Parera *et al.*, 2020
	SLBJ	4.14 (3.72)	
	SLLJ	6.63 (5.30)	
	CODS	1.83 (1.43)	
	SHL - Concentric	7.35 (5.72)	
	SHL – Eccentric	9.82 (9.65)	
	CRO – Concentric	9.31 (6.96)	
	CRO – Eccentric	11.18 (9.01)	
Tennis	SLCMJ	14.71 (10.05)	Madruga-Parera *et al.*, 2019

	SEBT – Anterior	4.76 (3.16)	
	SEBT – Posteromedial	4.22 (3.54)	
	SEBT – Posterolateral	5.49 (3.95)	
	SEBT – Composite	3.49 (2.29)	
	CODS	2.09 (2.24)	

SFL = step forward lunge; JFL = jump forward lunge; SEBT = star excursion balance test; SLCMJ = single-leg countermovement jump; SLBJ = single-leg broad jump; SLLJ – single-leg lateral jump; CODS = change of direction speed; SHL = shuffle lateral step with isoinertial device; CRO = crossover with isoinertial device.

2.6 Discussion

This literature review has explored the current knowledge and best practices regarding the monitoring of training load and use of IMUs within Badminton and other court-based sports. Based on the review of the current literature a number of potential gaps in knowledge have been highlighted which warrant further investigation.

2.6.1 <u>Key Findings from the Literature</u>

- Despite being one of the most popular sports in world (Kwan *et al.*, 2010), there is comparatively little published research assessing external training load in Badminton, and fewer still which directly address the youth population (Phomsoupha and Laffaye, 2014).

- Badminton has been found to have higher injury rates compared to both Rugby Union and Basketball (Weir and Watson 1996). In elite Badminton players, lower limb injuries accounted for 43% to 54% of all injuries sustained (Yung *et al.*, 2007; Guermont *et al.*, 2021) and in youth Badminton players 64% of injuries recorded were soft-tissue sprains and strains, with knee injuries accounting for 42% of lower limb injuries (Goh *et al.*, 2013).

- Lower limb asymmetries have been shown to be common in Badminton players. Greater width and thickness of the patellar and Achilles tendon in the dominant leg has been identified (Bravo-Sanchez *et al.*, 2019) as have larger dominant leg circumference (Petrinovic *et al.*, 2015). In a study of step forward lunge and jump lunge tasks by Badminton players, it was found that the dominant leg produced greater force across a range of metrics for both movements (Nadzalan *et al.*, 2017). This is of concern as lower limb asymmetry has been shown to be associated with poorer vertical jump performance and change of direction speed in youth racket sport athletes (Madruga-Parera *et al.*, 2020), as well as being linked to injury risk across a number of sports (Helme *et al.*, 2021).

- The use of IMUs may provide a reliable and valid mechanism for quantifying training load in Badminton. The appeal of the usage of IMUs for training load monitoring is clear as approaches traditionally used in field-based sports, such as GPS, are not possible indoors (Dellaserra *et al.*, 2014), while approaches such as LPS and multi-camera systems are prohibitively expensive (Cormack *et al.*, 2013) and require additional equipment which is often limited to a single court or venue (Gageler *et al.*, 2015).

- Badminton training load from IMUs has been found to be only correlated to the heart-rate measures at the High Intensity zone but not at the Low or Medium Intensity zones, with the latter showing a negative correlation. While the High

Intensity movements in Badminton, for example an Overhead Smash, would elicit a clear heart-rate response, 183.5 ± 5 bpm (Ghosh, 2008), the overall high work density observed in Badminton compared to field-based sports make it difficult to observe clear differences in the Low and Medium Intensity zones.

- In field-based sports upper trunk-mounted IMUs have been found to be a non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). This is likely due to the IMU being positioned far from the point of ground contact, therefore mechanical energy is absorbed and dissipated through the joints and body tissues between the foot and the IMU (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b).

- While movement classification has been conducted using a single trunk mounted IMU in Volleyball (Gageler *et al.*, 2015; Jarning *et al.*, 2015) and Cricket (McNamara *et al.*, 2015) this has not been as common place in the study of racket sports. Movement analysis in racket sports have often been proposed using multiple IMUs (Ahmadi *et al.*, 2009; Wang *et al.*, 2013), IMUs placed on the dominant arm (Connaghan *et al.*, 2011) or within the racket (Blank *et al.*, 2015; Anik *et al.*, 2016). A potential limitation to the concurrent use of multiple IMUs is that coaches may be reluctant to allow their athletes to wear IMUs during training and competition due to concerns regarding inconvenience to the athlete, lack of comfort and appearance (Luczak *et al.*, 2020).

2.6.2 Current Gaps in the Literature

- While there have been examples of intra-system (within system) reliability assessments, in both a laboratory setting and field setting with Australian Rules Football players (Boyd *et al.*, 2011), and test-retest reliability studies (Van Iterson *et al.*, 2016) there are at present a lack of studies regarding inter-system (between systems) reliability of IMUs. While similar studies have been conducted for the use of semi-automated tracking systems and GPS (Buchheit *et al.*, 2014), to date there are no similar studies regarding the IMUs within commercially available athlete management systems. Understanding the reliability is essential for practitioners to know if data obtained from one system is comparable to data obtained from a different system and therefore would be an area that requires further investigation

- A limitation to the application of Player Load, and similar calculations, is that training load is reported as a single number, which does not provide context as to how the load had been accrued. In a study of Rugby League, tri-axial training load was found to be unsuitable for assessing collision and tackling load when compared to dual-axial training load, as small increases in collision or tackling load were masked by the ground contact forces from the vertical axis (McClean *et al.*, 2018). In a Badminton context, load derived from medio-lateral accelerations from upper body rotations during an overhead smash and load derived from vertical accelerations from landings are combined into the overall Player Load score. From the current review of the literature, only Fish and Grieg (2014) reported separate Player Load, as a percentage of total Player Load, for each axis in Netball match-play. A similar approach may provide greater clarity on how load is accumulated in Badminton players. Load from the vertical axis may provide a more precise measure of lower limb loading by removing other loading parameters, such as acceleration from upper body rotations observed during a smash. Therefore, further study is warranted to evaluate whether accelerometer derived training load from a single trunk-mounted IMU, accrued on the vertical axis provides a more precise measurement of lower limb loading as compared to the overall load or load accrued from the antero-posterior and medio-lateral axis. If this is found to be the case, there are potential applications for use of axis specific training load metrics in the monitoring of Badminton athletes.

- Given the limitation of trunk mounted IMUs for ground reaction forces (Edwards *et al.*, 2018), a more direct measure may be required to monitor lower limb loading and to assess sport specific movement asymmetry in Badminton players, which has currently yet to be explored. In Rugby League, lower limb-mounted IMUs were able to quantify loads more directly that those mounted on the upper trunk and measure asymmetry during running (Glassbrook *et al.*, 2020b). Tibia-mounted IMUs have been found to provide good to excellent reliability for measurement of impact loading during Football (Soccer) specific acceleration-deceleration, plant and cut and change of direction tasks (Burland *et al.*, 2021). Lower limb-mounted IMUs may therefore provide a more direct measure of lower limb loading and assessment of movement asymmetry in Badminton, which may have potential implications for injury management and further study is warranted to assess the application of this technology within Badminton.

- While the use of multiple IMUs for movement classification in court-based sports has been highlighted in the literature review, a potential limitation is that coaches may be reluctant to allow their athletes to wear multiple IMUs during training and competition due to concerns regarding inconvenience to the athlete, lack of comfort and appearance (Luczak *et al.*, 2020). As collaboration between sport scientists and coaches is instrumental for the success of performance analysis systems (Hughes and Bartlett, 2002), a nuanced and symbiotic relationship between the sport scientist and the coach is required when planning data collection and developing performance analysis outputs (Bampouras *et al.*, 2012). It is therefore important to consider the perception of coaches towards the specific technology when assessing the potential use of multiple IMUs for performance analysis and/or load monitoring. With this context, further study is warranted to understand the perceptions of racket sports coaches towards the use of IMUs in training and competition. Understanding coaches' preferences towards the placement of IMUs would enable practitioners to propose solutions for regular athlete monitoring which are more likely to be accepted by coaches, which in turn may result in greater adherence by athletes.

2.7 Project Objectives

Based on the gaps highlighted within the literature review, the key objectives of this project are to:

- Assess the validity and reliability of IMUs for the measurement of Badminton specific movements;
- Assess the use of upper trunk-mounted IMUs to quantify axis specific training load in Badminton players;
- Understand the preference of racket sport coaches towards the use of IMUs during training and competition;
- Measure lower limb specific load and asymmetry to discriminate between Badminton players with and without unilateral or bilateral lower limb injury history.

2.7.1 Research Project Questions

The research questions and proposed study titles and study design for this thesis are outlined in Table 11.

Table 11 - Proposed Research Questions, Study Titles and Study Design

Research Questions	Study Title	Study Design
Are commercially available IMUs a reliable and valid tool for quantifying Badminton specific movements?	**Study 1:** Intra- and inter-system reliability of upper body-mounted IMUs for the measurement of Badminton specific training load	Reliability Study
Does axis specific accelerometer derived training load from an upper body-mounted IMU accurately quantify lower limb biomechanical load in Badminton players?	**Study 2:** Axis specific training load to quantify lower limb biomechanical loading in adolescent Badminton players	Correlational Study
What are coaches perceptions towards the use of IMUs in racket sports during training and competition?	**Study 3:** Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition	Quantitative Survey
Can limb specific load and asymmetry measurements from tibia-mounted IMUs discriminate between athletes with and without unilateral or bilateral lower limb injury history?	**Study 4:** Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history	Cross Sectional Observational Study

Chapter 3: Study One

3.1 Study One: Intra- and inter-system reliability of upper trunk-mounted Inertial Measurement Units for the measurement of Badminton specific training load

3.1.1 Research Question

Are commercially available IMUs a reliable tool for quantifying Badminton specific movements?

Parts of this study have been published in:

Wylde, M.J., Lee, M.B.C., Low, C.Y. and Callaway, A.J. 2018. Reliability and validity of GPS-embedded accelerometers for the measurement of badminton specific player load. *Journal of Trainology*, 7(2), 34-37 (see Appendix 1).

3.2 Introduction

As highlighted in the literature review, there are limitations to the current approaches used to monitor athletes in an indoor environment. While video-based time-motion analysis is convenient, practical and inexpensive, there are issues with the reliability of the data, especially if matches are being notated by different observers (Barris and Button, 2008). In addition, this method of movement analysis can be labour intensive (Dobson and Keogh, 2007) and time-consuming (Jarning *et al.*, 2015). While the use of GPS technology has been beneficial for field-based team sports, this technology can only be used in an outdoor setting with sufficient satellite coverage (Dellaserra *et* *al.*, 2014). A number of local positioning system (LPS) and semi-automated camera solutions are available but these are restrictive due to the additional hardware requirements (Gageler *et al.*, 2015) and the prohibitively high cost (Cormack *et al.*, 2013).

The use of IMUs provides a potentially useful tool for assessing athletes in an indoor environment. IMUs normally comprise three gyroscopes, three accelerometers and magnetometers with changes in orientation calculated based on a combination of these signals (Baca *et al.*, 2009). IMUs allow athletes to perform normal movements with little encumbrances in their normal training environment, instead of in a sport science or biomechanics laboratory, which maintains the ecological validity of data which is collected (Zak., 2014). Many of the commercially available athlete tracking systems have inbuilt IMUs which has been used to supplement the GPS data through calculating accelerometer derived training load. These athlete tracking systems include Catapult Innovations (Melbourne, Australia), GPSport (Canberra, Australia), Statsports (Newry, Northern Ireland, UK) and VX Sport (Visuallex Sport International, Lower Hutt, New Zealand). The IMUs within these athlete tracking systems have been used to quantify athlete loading in indoor court-based sports such as Badminton (Abdullahi *et al.*, 2019), Basketball (Montgomery *et al.*, 2010; Scanlan *et al.*, 2014), Netball (Cormack *et al.*, 2013; Chandler *et al.*, 2014; Fish and Grieg, 2014) and Ice Hockey (Van Iterson *et al.*, 2017) and to assess jump frequency in Volleyball (Gageler *et al.*, 2015).

The IMUs within the MinimaxX S4 units (Catapult Innovations, Melbourne, Australia) have been shown to be reliable for use with sports as diverse as Canoe Kayak

(Janssen and Sachlikidis, 2010), Australian Football (Boyd *et al.*, 2011) and Mixed Martial Arts (Hurst *et al.*, 2014) while the Optimeye S5 units (Catapult Innovations, Melbourne, Australia) have been shown to be reliable for measuring athlete loading in Ice Hockey (Van Iterson *et al.*, 2017) and Handball (Luteberget *et al.*, 2018).

To date there are no studies assessing the reliability of upper trunk-mounted IMUs for the assessment of Badminton specific movements. It is vital that the sport-specific reliability of a system or technology is demonstrated, and that the data are assessed in a way that is compatible with the intended use (Hughes, 2008). In an elite sport setting, the reliability of systems and technologies being used becomes of greater importance as decisions on training prescription, team selection and game tactics may be made by athletes and/or coaches based on the information provided by these systems (O'Donoghue and Longville, 2004). In Badminton, where there are high incidences of lower limb injuries (Yung *et al.*, 2007; Guermont *et al.*, 2021), which may be preventable with appropriate prescription of training loads (Bourdon *et al.*, 2017), the use of reliable and valid systems to accurately measure loading is essential to provide coaches and practitioners with high quality information from which to make decisions. Therefore, the purpose of this study is to assess the reliability of the IMUs embedded within the VX Sport Log units to quantify Badminton specific movements. Firstly, the intra-system reliability will be assessed within the VX Sport Log system. Secondly, the inter-system reliability will be assessed between the VX Sport Log and Catapult Optimeye S5 systems.

3.3 Justification of Method

Measurement error, which results in observed values of measure differing from the true value, can be classified as construct (or concurrent) validity and reliability. Construct validity concerns the agreement between the observed value and the true value, while reliability concerns the reproducibility of the observed value (Hopkins, 2000). In the context of performance analysis or athlete monitoring systems, reliability can be defined as the consistency of the measurements made using a system (Wilson and Batterham, 1999). A common method for assessing reliability is through the use of an intra-operator reliability test, where the same operator or system is tested against itself. For example, in the context of video-based time-motion analysis, this would involve an operator using the same system to assess the same matches on multiple occasions to ensure that the variation between these assessments was low enough for the data obtained to be considered reliable (O'Donoghue, 2007).

For the assessment of the reliability of an athlete monitoring system this would involve either an athlete conducting the same set of movements twice, each time wearing a single IMU with the data from each trial compared, or through conducting a set of movements while wearing 2 or more IMUs, and the data from these IMUs being compared. An example of the former would be the test-retest method used to assess the reliability of the Catapult Optimeye S5 system for use with Ice Hockey specific movements, where each participant wore a single IMU and performed two bouts of nine ordered tasks (Van Iterson *et al.*, 2017). An example of the latter would be the method used to assess the reliability of the Catapult Optimeye S5 system for use in Handball, where each participant wore two IMUs for the duration of a single training session consisting of seven distinct tasks (Luteberget *et al.*, 2018). Given the high degree of movement variability seen in Badminton, the latter option, in which each participant wears two IMUs, would be more appropriate for assessing reliability as it is unlikely that the participants would be able to precisely replicate their movements if a test-retest method was applied.

While the use of intra-operator/system reliability assessments are common within the literature and applied setting, such assessments in isolation may not be sufficient to confirm the construct validity of a system (O'Donoghue, 2007). Even if a good level of reliability is achieved in an intra-system reliability assessment, this only indicates that the system is consistent in producing the same results. It does not indicate if the system is providing agreement between the observed value and the true value. While intra-system tests do have a place in ensuring systems produced consistent results, it is essential that an inter-system reliability test is also carried out to assess the construct validity of a system.

Within the current literature there is a lack of inter-system reliability assessments of the IMUs used within commercially available athlete monitoring systems. While similar studies have been conducted for the use of semi-automated tracking systems and GPS, where a number of systems were compared against a "gold standard" of timing gates (Buchheit *et al.*, 2014), this has not been the case with the study of IMUs. Given the consistent high levels of reliability recorded for the Catapult system (Janssen and Sachlikidis, 2010; Boyd *et al.*, 2011; Hurst *et al.*, 2014; Van Iterson *et al.*, 2017; Luteberget *et al.*, 2018) this can be considered the "gold standard" from which the assessment of the VX Sport system can be made to confirm the inter-system reliability.

In reliability assessments of IMUs, participants are often required to perform specific tasks or drills to ensure desired sport-specific movements are assessed to establish construct validity (Boyd *et al.*, 2011; Hurst *et al.*, 2014; Van Iterson *et al.*, 2017; Luteberget *et al.*, 2018). However, to ensure construct validity, measures of physical activity should relate specifically to the particular purpose under investigation and to the participants with whom the measure will be used (Mahar and Rowe, 2002). In a Badminton context, the environment with the highest construct validity would be simulated match-play. However, within such an environment it would be difficult to ensure all required movements are performed and, even with the use of a shuttlecock feeder, there would be some level of variability. Therefore, the Badminton specific incremental test (Wonisch *et al.*, 2003) may provide a more consistent basis for assessment while still including key Badminton-specific movements (around court movement, lunge and jump smash). In addition, as the speed of the test increases incrementally, this allows for the reliability of the IMUs to be assessed under different movement speeds.

As highlighted in the literature review, the most common IMU placement is located at the upper trunk, between the scapulae (Boyd *et al.*, 2011; Fish and Grieg, 2014; Gageler *et al.*, 2015; Van Iterson *et al.*, 2017; Luteberget *et al.*, 2018). The key reason for this placement is to ensure the safety of the athletes and to protect the unit in high collision sports, such as both Rugby codes and Australian Rules Football. However, in Badminton, and other racket sports, collisions are uncommon and therefore the safety aspect of the IMU placement becomes less of a consideration. In Badminton and Volleyball studies, IMU placement at the lower trunk has been used (Dieu *et al.*, 2014; Jarning *et al.*, 2015). The assumption in placing the IMU at the lower trunk is that as this is closer to the centre of mass it therefore represents a better estimation of overall body load (Simons and Bradshaw, 2016). However, in a study of Gymnastics landing, where IMU placement at the upper and lower trunk were compared, it was found that the upper trunk placement was better able to discriminate between the various heights during drop landings (Simons and Bradshaw, 2016). The differences between the upper and lower trunk measures were attributed to greater soft tissue movement at the lower trunk. In addition, in a study of Rugby League players it was found that IMUs placed within the purpose-built vest provided by the manufacturer ensured greater reliability and validity when compared to IMUs housed in pockets within the players' shirts (McLean *et al.*, 2018). Based on these findings, during this study IMUs will be placed on the upper trunk, between the scapulae in the manufacturer provided harness.

The majority of accelerometers housed within athlete monitoring systems have a sampling frequency of 100 Hz, equating to 100 data points per second (McLean *et al.*, 2018). In general, many accelerometer manufacturers use a frequency in the range of 100 to 159 Hz, as this range falls within the region of flat response, neither too high nor too low. Frequencies within this range offer the lowest uncertainty, as at the high and low ends of the accelerometer's frequency response the uncertainty will increase. For example, in a study where accelerometer data was sampled at frequencies ranging from 20 to 100 Hz to assess human movement, it was found that changing sampling density to 100 Hz increased the robustness of signal reconstruction, compared to the lower sampling rates (John *et al.*, 2019). In a study utilising IMUs placed on the dominant arm and racket to identify Badminton specific movements, it was found that a sampling frequency of 100 Hz provided the greatest accuracy, 82%, compared to 77% for 25 Hz and 79% for 50 Hz (Steels *et al.*, 2020). Given the common use of 100 Hz as a sampling frequency within the literature and the robustness and accuracy of this frequency, a sampling frequency of 100 Hz will be used within this study.

For the assessment of IMU reliability in sport specific settings, sample sizes of between eight and ten athletes have been used in the literature (Boyd *et al.*, 2011; Hurst *et al.*, 2014; Van Iterson *et al.*, 2017). For this study the sample size was based on a desired reliability coefficient of >= 0.85, alpha at 0.05, power at 80% and was calculated using the tables provided in Algina and Olejnik (2003), resulting in a minimum required sample of eight per group.

For the assessment of both the intra- and inter-system reliability the coefficients of variation (CV%) and intra-class correlation coefficient (ICC) calculations were selected. Both measures have been commonly used to assess IMU reliability in a sports context (Choukou *et al.*, 2013; Gindre *et al.*, 2015; Van Iterson *et al.*, 2017).

CV% is a dimensionless method for quantifying the degree of variability relative to the mean and has been widely used in many areas such as science, medicine, engineering, economics, and sport (Panichkitkosolkul, 2013). For many measurements in sport science, the typical error increases as the value of the measure increases. In a Badminton context, the absolute load for a post-pubertal player would be larger compared to that of a pre-pubertal player (for example, 1900 Arbitrary Units (AU) vs 700 AU). As a result, the absolute differences between accelerometer derived training load for the post-pubertal player may appear larger than for the pre-pubertal player (50 AU vs 15 AU). Although the absolute values of the typical errors may differ, the values expressed as a percentage of their respective means are similar (2 to 2.5%). As CV% is a dimensionless measure, it allows for this direct comparison of the reliability of measures irrespective of calibration or scaling (Hopkins, 2000), thus facilitating the comparison between the IMUs regardless of the developmental stage of the Badminton players being tested.

ICC is a value for describing the correlations within a class of data (for example, correlations within repeated measurements of weight), rather than correlations between two different classes of data (for example, the correlation between weight and length) (Lijequist *et al.*, 2019). There are several versions of ICC which can be calculated depending on a number of factors: one-way random effects, two-way random effects, two-way mixed effects. For the purpose of this study a two-way random effects ICC (3,1) will be utilised. While paired t test and Bland-Altman plots are methods for analysing agreement and Pearson correlation coefficient is a measure of correlation, ICC reflect both the degree of correlation and agreement between measurements (Koo and Li, 2016).

3.4 Method

With institutional ethical approval, 15 participants were recruited for the data collection (age 26.7 ± 5.6 y, height 1.67 ± 0.77 m, mass 61.6 ± 4.7 kg). Each participant was a recreational Badminton player with a minimum of 5 years playing experience. Each participant was provided with a participant information sheet (see Appendix 2) and was required to complete an informed consent form prior to the data collection. Eight participants were tested wearing two VX Sport Log units (Visuallex Sport International, Lower Hutt, New Zealand) and nine participants were tested wearing one VX Sport Log unit and one Catapult Optimeye S5 unit (Catapult Innovations, Melbourne, Australia). Each unit was placed between the scapulae in purpose-built harnesses and each participant was required to wear two vests, one for each unit. For each test the IMUs embedded within these units had a sampling frequency of 100Hz.

Each participant was asked to perform a warm up of their choice prior to the commencement of the data collection. Immediately before starting the data collection the participants were instructed to perform three vertical jumps to aid the synchronisation of the data (Callaway and Cobb, 2012). The participants were instructed to perform the Badminton specific incremental test (Wonisch *et al.*, 2003) in one half of a Badminton court, see Figures 5 and 6. From a central point the participant started moving following a signal given as a computer-generated beep. The participant moved 3 m forward at a 45-degree angle to a marker at the right side of the court, touched the top of the net with their Badminton racket and moved immediately back to the central point. On the next signal the participant moved to a second marker at the left side of the court, touched the top of the net with their racket and moved back to the central point. On the next signal the participant moved backwards to a third marker 3 m behind the central point, performed a simulated smash then returned to the central marker. Once the participant returned to the central point the procedure repeated and continued until voluntary exhaustion. Signals were given from a pacer with the velocity at the beginning of the test being 0.60 ms-1, with six signals per minute. The velocity increased every minute by 0.10 ms-1, with one additional signal per minute.

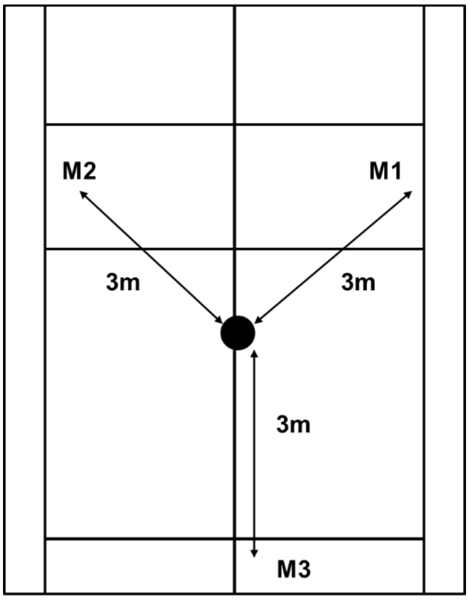


Figure 5 - Diagram of Badminton Specific Incremental Fitness Test (Wonisch *et al.*, 2003)

Figure 6 - Data Collection Using the Badminton Specific Incremental Fitness Test (Wonisch *et al.*, 2003)

Upon completion of the test protocol the data were extracted using the accompanying software of the two systems. The raw data was filtered in Matlab (MathWorks, Natick, MA, USA) at 10Hz using a 3rd order Butterworth low pass filter. The filtered data was mean centred in Microsoft Excel (Redmond, WA, USA) and manually synchronised by aligning the three vertical jumps within the datasets. The maximum accelerations and decelerations for each axis were used as the first point of comparison. In addition, the training load of each axis was calculated using a modified vector magnitude calculation (Boyd *et al.*, 2011). The equation for the respective axis were are outlined below (Equation 3):

$$Vertical\ Load = \sqrt{\frac{(az_1 - az_{-1})^2}{100}} \qquad Antero - Posterior\ Load = \sqrt{\frac{(ay_1 - ay_{-1})^2}{100}} \qquad Medio - Lateral\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2}{100}}$$

Equation 3: Vertical, Antero-Posterior, Medio-Lateral Load calculations

To assess the intra- and inter-system reliability, CV%, derived from the typical error of the log-transformed values with a 90% confidence limit, and two-way random effects ICC (3,1) calculations were selected (Hopkins, 2000). For CV% a value of <10 was deemed “Very Good”, 10-20 “Good”, 20-30 “Acceptable” and >30 “Not Acceptable”. For the ICC calculations the following descriptors were used: “Poor” <0.40, “Fair” 0.40-0.59, “Good” 0.60-0.74, “Excellent” 0.75-1.00 (Cicchetti, 1994).

3.5 Results

A high level of agreement between the two VX Sport Log units with all CV% under the 10% threshold and "Excellent" ICC observed for all measures, see Table 12 and Figure 7.

Table 12 - Intra-System Reliability between VX Sport Log Units (N=8)

		Max Acceleration ($m/s^2 \pm$ SD)	Max Deceleration ($m/s^2 \pm$ SD)	Vector Magnitude (AU ± SD)
Vertical	Unit 1	2.06 ± 0.25	-1.48 ± 0.16	119.42 ± 29.13
	Unit 2	2.12 ± 0.22	-1.49 ± 0.18	123.03 ± 30.84
	CV%	1.5	1.6	1
	ICC	0.980 *Excellent*	0.988 *Excellent*	0.996 *Excellent*
Antero-posterior	Unit 1	1.12 ± 0.27	-1.68 ± 0.24	81.26 ± 15.45
	Unit 2	1.15 ± 0.31	-1.66 ± 0.22	77.41 ± 14.14
	CV%	5.1	1.9	2.3
	ICC	0.980 *Excellent*	0.961 *Excellent*	0.979 *Excellent*
Medio-lateral	Unit 1	1.28 ± 0.26	-1.22 ± 0.24	50.88 ± 6.85
	Unit 2	1.33 ± 0.24	-1.23 ± 0.22	54.03 ± 8.36
	CV%	3.2	3.5	2.3
	ICC	0.975 *Excellent*	0.977 *Excellent*	0.958 *Excellent*

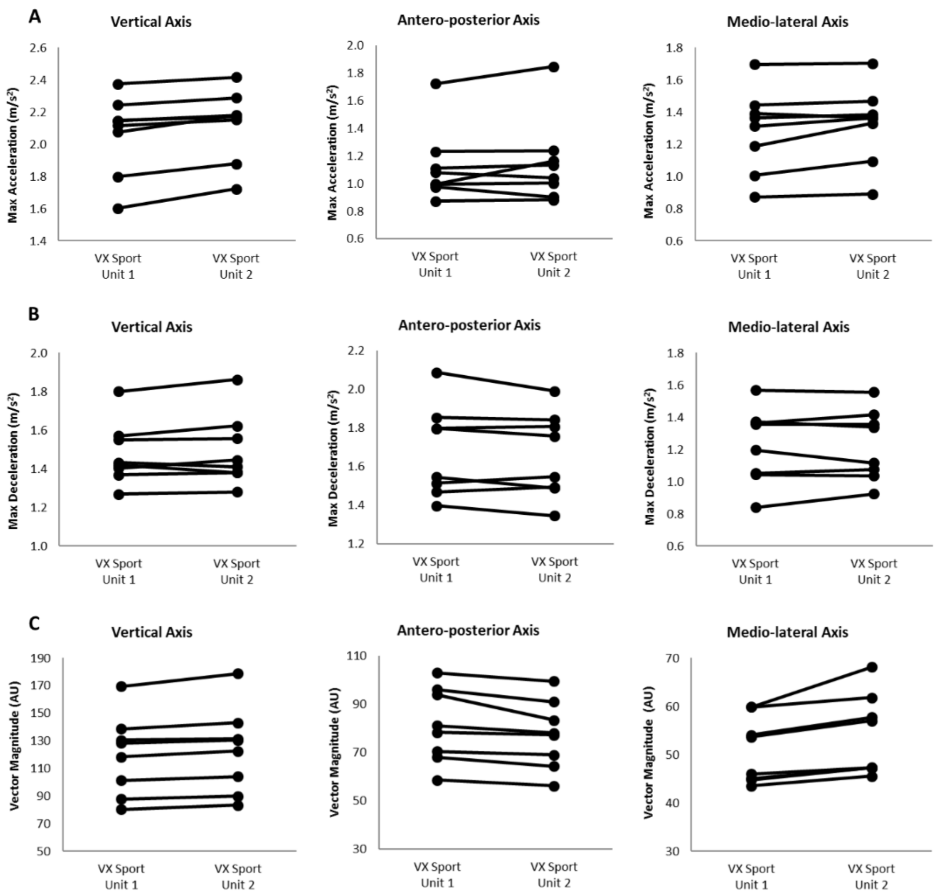


Figure 7 - Intra-System Comparison between VX Sport Log units. a) Max acceleration, b) Max Deceleration, c) Vector Magnitude.

An acceptable level of agreement was also observed between the VX Sport Log and Catapult Optimeye units. For all comparisons CV% below 10% were recorded and “Excellent” ICC values were recorded, see Table 13 and Figure 8.

Table 13 - Inter-System Reliability between VX Sport Log and Catapult Optimeye S5 Units (N=9)

		Max Acceleration (m/s ± SD)	Max Deceleration (m/s ± SD)	Vector Magnitude (AU ± SD)
Vertical	VX Sport	1.98 ± 0.20	-1.49 ± 0.15	106.55 ± 24.88
	Catapult	2.05 ± 0.21	-1.52 ± 0.17	108.15 ± 25.55
	CV%	3.3	2.8	3.8
	ICC	0.897 *Excellent*	0.937 *Excellent*	0.970 *Excellent*
Antero-posterior	VX Sport	1.04 ± 0.20	-1.58 ± 0.21	70.85 ± 20.43
	Catapult	1.05 ± 0.19	-1.54 ± 0.24	70.66 ± 22.79
	CV%	5.2	4.4	6.1
	ICC	0.934 *Excellent*	0.925 *Excellent*	0.956 *Excellent*
Medio-lateral	VX Sport	1.32 ± 0.18	1.13 ± 0.25	42.31 ± 7.91
	Catapult	1.33 ± 0.24	1.22 ± 0.24	48.57 ± 7.56
	CV%	7.3	4.5	7.1
	ICC	0.785 *Excellent*	0.965 *Excellent*	0.828 *Excellent*

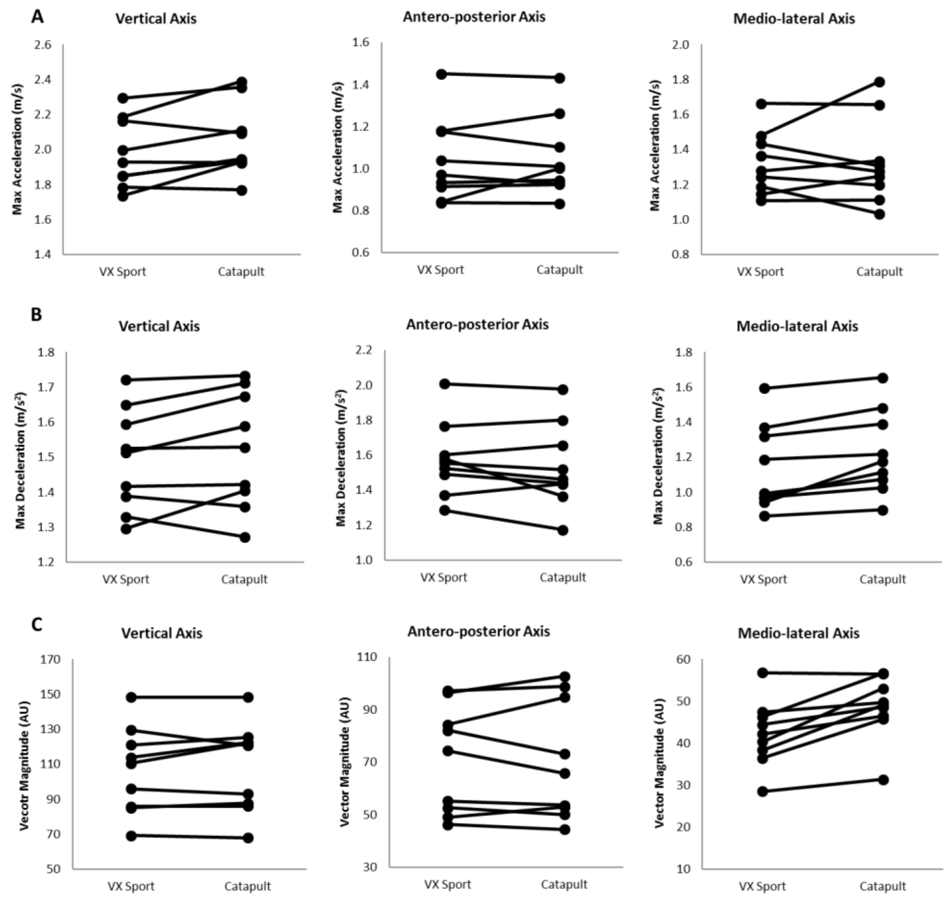


Figure 8 - Inter-System Comparison between VX Sport Log and Catapult Optimeye S5 units. a) Max acceleration, b) Max Deceleration, c) Vector Magnitude.

3.6 Discussion

The purpose of this study was to assess the intra-system and inter-system reliability of the VX Sport Log embedded IMUs to measure Badminton specific movements. Based on the results from the intra-system reliability assessment, where two units from the VX Sport system were compared, it can be determined that the IMUs within the VX Sport Log units offer a reliable means to compare acceleration and training load of

Badminton specific movements between different athletes or the same athlete over multiple training sessions. An acceptable level of inter-system reliability was also found between the VX Sport Log and Catapult Optimeye S5 systems, although this was higher than that recorded in the intra-system reliability test. These results demonstrate that it is reliable to use data from different IMU systems (namely VX Sport Log and Catapult Optimeye S5) to compare Badminton specific movements. However, improved levels of reliability are achieved if the same system is used.

While the level of inter-system reliability is acceptable, this agreement was not as strong as the intra-system reliability and the potential reason for this warrants investigation. Firstly, the two units used have different dimensions, meaning that the exact positioning of the IMU within the unit would be different between the two systems, see Figure 9.

Figure 9 - Dimensions of VX Sport Log and Catapult Optimeye S5 Athlete Tracking Units

Secondly, in the design of the data collection, the participants were required to wear two vests, one for each unit. One vest was worn over the top of the other and in most cases the second vest was a size larger than the first vest. For example, if the first vest was size “Small” the second outer vest would be size “Medium”. While this was necessary for the comfort of the participants, it may have resulted in additional movement of the outer unit which was placed in the larger vest. In a study of Rugby Union players, it has been suggested that the elasticised harness of the IMU was one of the major contributors to extraneous accelerometer magnitudes (Edwards *et al.*, 2018). In addition, a study of Rugby League found that data obtain from units worn in a pouch in the player's jersey had lower construct validity than data obtained from a unit worn in the manufacturer's purpose-built vest, due to the former causing greater incidental unit movement (McLean *et al.*, 2018). The highest CV% were observed in the media-lateral axis during the inter-system reliability tests. In the intra-system reliability, the media-lateral axis also demonstrated the poorest reliability for two of the three measures. This would suggest that the outer units experienced greater movement from body rotations during the reliability assessment. This may be due to the looser fitting outer vest experiencing more movement during upper body rotations or due to the greater rotational torque acting on the outer unit as it is further away from the point of rotation.

Notwithstanding the issues mentioned above, an additional cause of the poorer inter-system reliability was the inconsistent sampling frequencies observed between the two systems. While at the outset of the data collection there was no difference between the two units, a disparity became apparent as the data collection progressed. The following Bland-Altman plots in Figure 10 represent the first and final 10 seconds recorded in one of the trials. These plots demonstrate that the difference between the two systems increased as the data collection progressed. This suggests that one, or both of the units, was not recording at a true 100 Hz.

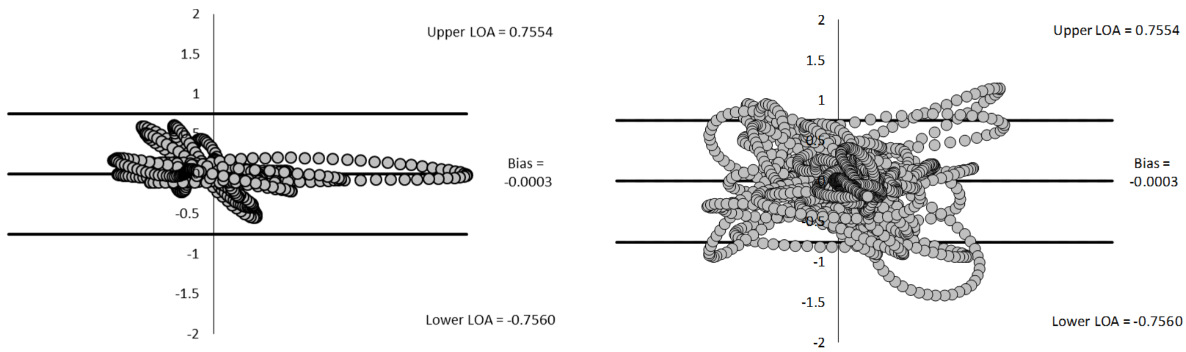


Figure 10 - Bland-Altman Plots of First and Last 10 seconds of the Data Collection

While the disparity in the sampling frequencies did not lead to unacceptable level of inter-system reliability, this may have been due to the relatively short duration of the reliability assessment. The disparity between the two sampling frequencies could result in more significate differences if used for a longer duration, such as for the full duration of a Badminton match. While it was not possible to ascertain which of the systems was not recording at a true 100Hz, it was observed that there was a 0.25% difference between the two sampling frequencies. Once this error was established, it was possible to resample the data using MatLab so that both datasets were sampled at the same frequency. The Bland-Altman charts in Figure 11 represent the first and last 10 seconds of the data collection after resampling and show a smaller difference throughout the trial.

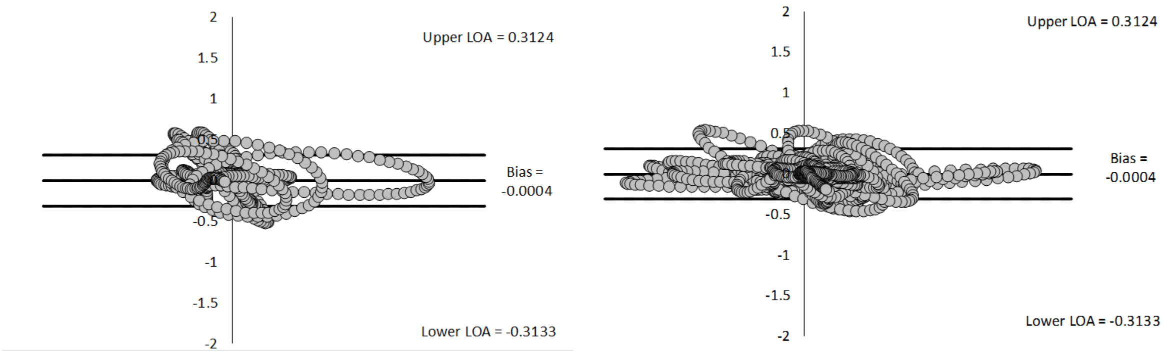


Figure 11 - Bland-Altman Plots of First and Last 10 seconds of the Data Collection After Resampling

This approach should be used when seeking to compare data collected from different brands of athlete tracking system to ensure that the reliability of the results is as high as possible.

3.7 Conclusion

The intra-system reliability for the VX Sport Log system was high with CV% of below 5% in 8 of our 9 comparisons and “Excellent” ICC for all measures. The inter-system reliability between the VX Sport Log and Catapult Optimeye S5 systems was also acceptable, with CV% below 10% and “Excellent” ICC values. However, there were larger differences observed in the inter-system reliability compared to the intra-system reliability. These differences may have been due to the relative size of the units, the placement of the units within two vests and the disparity in sampling frequencies due to one or both systems not sampling at a true 100Hz. In circumstances where longer data collection duration was required, resampling the data so that data from both systems was at the same sampling frequency would provide improved reliability.

Based on the results from this study, it is reliable to use data from different IMU systems (namely VX Sport Log and Catapult Optimeye S5) to compare Badminton specific movements. However, higher levels of reliability are achieved if the same system is used. For subsequent studies in this thesis, the same brand of athlete tracking system will be used. This will eliminate as much error as possible and ensure a highest attainable level of reliability.

3.8 Future Study

Study 1 has demonstrated that upper trunk-mounted IMUs provide a reliable method for assessing Badminton specific movements, in particular when the same brand of athlete tracking system is used. Given the high prevalence of lower limb injuries in Badminton, with injury rates of 11.6 per 1,000 of playing hours in matches (Guermont *et al.*, 2021) and lower limb injuries accounting for between 43% and 54% of all injuries (Yung *et al.*, 2007; Guermont *et al.*, 2021), the use of upper trunk-mounted IMUs would potentially provide a method for quantifying training load and allow for the prescription of more optimal loading to reduce injury rates.

In Badminton, accelerometer derived training load from a single upper trunk-mounted IMU has been compared to internal load measures derived from heart-rate (Abdullahi *et al.*, 2019). It was found that the training load value was only correlated to the heart-rate measures at the High Intensity zone but not at the Low or Medium Intensity zones, with the latter showing a negative correlation. The authors concluded that while the High Intensity movements in Badminton, for example an Overhead Smash, would elicit a clear heart-rate response, 183.5 ± 5 bpm (Ghosh, 2008), the overall high work density observed in Badminton compared to field-based sports made it difficult to observe clear differences in the Low and Medium Intensity zones.

The limitation with this approach is that training load is reported as a single number with no way of differentiating how this load was accumulated. In Rugby League, load taken from the antero-posterior and medio-lateral axis only has been shown to be a more accurate measure of athlete loading, as the inclusion of vertical load masks small increases in collision or tackling load (McClean *et al.*, 2018). In a Badminton context, load derived from medio-lateral accelerations from upper body rotations during, for example, an overhead smash, may similarly mask lower limb loading. Axis specific training load has been reported in other court-based sports, with each axis reported as a percentage of total load in Netball match-play (Fish and Grieg, 2014). A similar approach may provide greater clarity into how load is accumulated by Badminton players in training and competition. Load from the vertical axis may provide a more precise measure of lower limb loading by removing other loading parameters, such as upper body rotation. The aim of Study 2 will therefore be to evaluate whether load from the vertical axis provides a more precise measurement of lower limb loading as compared to total load or load from the antero-posterior and medio-lateral axis.

An update to the research questions and proposed study titles and study design with the key findings from Study 1 are outlined in Table 14.

Table 14 - Proposed Research Questions, Study Titles, Study Design and Key Findings

Research Questions	**Study Title**	**Study Design**	**Key Findings**
Are commercially available IMUs a reliable and valid tool for quantifying Badminton specific movements?	**Study 1:** Intra- and inter-system reliability of upper body-mounted Inertial Measurement Units for the measurement of Badminton specific training load	Reliability Study	1. Different commercially available IMUs are reliable to compare Badminton specific movements. 2. Higher levels of reliability are achieved when the same IMU system is used.
Does axis specific accelerometer derived training load from an upper body-mounted IMU accurately quantify lower limb biomechanical load in Badminton players?	**Study 2:** Axis specific training load to quantify lower limb biomechanical loading in adolescent Badminton players	Correlational Study	
What are coaches perceptions towards the use of IMUs in racket sports during training and competition?	**Study 3:** Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition	Quantitative Survey	
Can limb specific load and asymmetry measurements from tibia-mounted IMUs discriminate between athletes with and without unilateral or bilateral lower limb injury history?	**Study 4:** Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history	Cross Sectional Observational Study	

Chapter 4: Study Two

4.1 Study Two: Axis specific training load to quantify lower limb biomechanical loading in adolescent Badminton players

4.1.1 Research Question

Does axis-specific accelerometer derived training load provide a more precise measurement of lower limb loading as compared to total training load in adolescent Badminton players?

Parts of this study have been published in:

Wylde, M.J., Kumar, B., Low, C.Y. and Callaway, A.J. 2019. Axis specific player load to quantify lower limb biomechanical loading in adolescent Badminton players. *International Journal of Racket Sports Science*, 1(1), 37-44 (see Appendix 3).

4.2 Introduction

Study 1 demonstrated that upper trunk-mounted IMUs provide a reliable method for assessing Badminton specific movements, in particular when the same brand of athlete monitoring system is used. Trunk-mounted IMUs may therefore provide a reliable method for assessing athlete loading during training and competition. Monitoring an athlete's loading is essential for determining whether an athlete is adapting to a training programme, understanding the need for recovery and reducing injury risk (Bourdon *et al.*, 2017). While the optimal "dose" of load will create adaptations that will result in performance improvement, too little will blunt adaptations and too much will result in overuse injury and illness (Vanrenterghen *et al.*, 2017).

Understanding how load is accumulated is important as adaptations from different forms of loading occur at different timeframes. For example, recovery from physiological loading may take only a few hours for a well-trained athlete, while recovery from biomechanical loading may take a few days. The danger would occur when an athlete returns to training when recovered from the physiological load but under recovered from the biomechanical load, which may result in overuse injury. Conversely, if an athlete only continues physiological loading when fully recovered from the biomechanical load, the physiological system may be undertrained which would result in a performance decrement (Vanrenterghen *et al.*, 2017).

Accelerometer derived training load from a single upper trunk-mounted IMU has been compared to internal load measures derived from heart-rate in elite Badminton players (Abdullahi *et al.*, 2019). In this study it was found that the training load value was only correlated to the heart-rate measures at the High Intensity zone but not at the Low or Medium Intensity zones. The limitation with this approach is that training load is reported as a single number with no way of differentiating how this load was accumulated. While the majority of studies report training load as a single score, Fish and Grieg (2014) reported separate training load values, as a percentage of total load, for each axis in Netball match play. In a Netball context, it was found that a similar pattern in training load was seen across the different axes, with Centres recording the highest training loads on each axis and Goal Shooters and Goal Keepers recording the lowest training loads on each axis. Due to the positional movement constraints in Netball, where Centres can operate in all thirds of the court (except the Goal Circle) while Goal Shooters and Goal Keepers are constraint to one third, the similarities in training load across axes would be expected. However, as movement constraints are not used in Badminton, a similar approach may provide greater clarity as to how load is accumulated by youth Badminton players. Training load from the vertical axis may provide a more precise measure of lower limb biomechanical loading by removing other loading parameters, such as upper body rotation observed during a smash.

The aim of this study is to evaluate whether training load from the vertical axis provides a more precise measurement of lower limb biomechanical loading as compared to total training load or the training load from the antero-posterior and medio-lateral axis.

4.3 Justification of Method

As highlighted in Study 1, IMUs placed at the upper trunk are common in many field- and court-based sports (Boyd *et al.*, 2011; Fish and Grieg, 2014; Gageler *et al.*, 2015; Van Iterson *et al.*, 2017; Luteberget *et al.*, 2018*)* and placement at the upper truck provides more accurate assessment of landings compared to IMUs located at the lower trunk (Simons and Bradshaw, 2016). Further to this, the results from Study 1 highlight that upper trunk-mounted IMUs provide a reliable and valid method for assessing Badminton specific movements. Therefore, the placement of the IMUs at the upper trunk will continue to be used in Study 2.

A major limitation of the use of IMUs for training load monitoring is that training load is often reported as a single number, being the accumulated accelerometer derived load from all three axes (Montgomery *et al.*, 2010; Cormack *et al.*, 2013; Scanlan *et al.*, 2014; Abdullahi *et al.*, 2019). This approach allows for easy translation into practice by coaches and athletes by offering "one number to describe the session" (Catapult

Innovations, Melbourne, Australia). However, there is a danger that this represents an oversimplification of the movement which is being assessed. As the accelerations for all axes are combined to provide a single training load score, high accelerations in one axis may mask smaller variations in another axis. In a study of Rugby League, it was found that accelerations from the vertical axis amassed during running, masked smaller changes in collision and tackling load (McClean *et al.*, 2018). Therefore, it was found that isolating the antero-posterior and medio-lateral axes provided a better measure of the collision and tackling load. Based on this premise, isolating the vertical axis may provide a more direct measure of lower limb loading in Badminton.

In court-based sports, reporting of axis specific training loads is uncommon. In a study of Netball, axis specific training load was reported as a percentage of the total load (Fish and Grieg, 2014). Reporting the absolute load from each axis may provide greater insight into how total load is accrued. The assumption is that training load from the vertical axis will provide a more accurate measure of lower limb loading, as load from this axis would likely be accrued from landing, lunging and change of direction tasks. By contrast, load from the antero-posterior and medio-lateral axis (and by extension total training load) may be impacted from upper body rotations during, for example, an overhead smash movement and may provide a less accurate measure of lower limb loading, compared to vertical load.

To assess whether vertical axis specific training load provides a more direct measure of lower limb loading in Badminton players, a comparison measure is required. RPE is a commonly used measure in Badminton to provide an overall assessment of the internal load experienced by an athlete during training or competition (Gosh, 2008;

Alcock and Cable, 2008; Fernandez-Fernandez *et al.*, 2013). However, global RPE may represent an oversimplification of the various internal and external loads acting on an athlete during movement, which in turn could be insufficient to capture the whole range of exercise-related perceptual sensations (Hutchinson and Tenenbaum, 2006). To overcome this oversimplification, differential RPE, where RPE for "local" muscle fatigue and "central" breathlessness are measured separately, may provide a more sensitive method for the evaluation of training in competitive sport environments (Weston, 2013). The use of differential RPE in a bicycle-based fitness test found that while correlated, for the majority of participants (71%) leg fatigue was the dominant symptom at the test conclusion and not breathlessness (Borg *et al.*, 2010). This demonstrated that even under test to exhaustion conditions, participants were able to differentiate between lower limb and overall fatigue.

In the study of Australian Rules Football, GPS measures obtained from an athlete monitoring system were compared against differential RPE localised to the lower limbs (RPE-L), "central" breathlessness (RPE-B), physical exertion (RPE-M) and technical demands (RPE-T) (Weston *et al.*, 2015). Differential RPE for the lower limbs (RPE-L) and breathlessness (RPE-B) have also been applied to the study of Rugby Union, in comparison to various sprint, jump and endurance tests (McLaren *et al.*, 2018), and with Football (Soccer) players during two incremental-exercise protocols (McLaren *et al.*, 2016). In the latter study, it was found that differential RPE enhanced the sensitivity of internal-load measurement (McLaren *et al.*, 2016).

Understanding how load is accrued is essential for managing adaptations and in the design of training programmes. In a Badminton context, differential RPE provides a method for isolating breathlessness (perceived physiological load) and lower limb fatigue (perceived biomechanical load) which then enables assessment of how accelerometer derived training load correlates with each. This approach will therefore be used within Study 2 with the axis specific training load being compared against the differential RPE for breathlessness and lower limb fatigue.

Studies utilising differential RPE as a tool for comparison have used sample sizes of 20 and 22 participants (McLaren *et al.*, 2016; McLaren *et al.*, 2018), while studies of training load data obtained from IMUs in Badminton have used a sample size of 21 participants (Abdullahi *et al.*, 2019). For this study the sample size was based on an expected correlation of >= 0.6, alpha at 0.05, power at 80% and was calculated using the tables provided in Algina and Olejnik (2003), resulting in a required sample size of 19.

As highlighted in Study 1, a sampling frequency for accelerometer data of 100 Hz is common within the sport science literature (McLean *et al.*, 2018) and provides robust and accurate data (John *et al.*, 2019; Steels *et al.*, 2020). A sampling rate of 100 Hz will therefore continue to be used within this study.

The data collected for the training load and RPE (RPE-L and RPE-B) measures were found to be non-normally distributed. This was assessed using the Shapiro-Wilk test (see Table 15). As a result, non-parametric measures were required to analyse the data. To calculate the difference between groups, the Mann-Whitney U test was selected. The Mann-Whitney U test looks for a significant degree of separation between two samples and starts with the null hypothesis that the two samples come from the same population (Rouncefield, 1998). In the context of this study, this would mean that the assumption is that both groups experience the same training load and RPE.

The assess the correlations between the training load and RPE measures the Spearman's Rank Correlation Coefficient was selected. Spearman's Rank Correlation Coefficient measures the degree of relationship between two ranked variables with the assumption of a monotonic relationship between the two variables (Sakinc *et al.*, 2017). This test is suitable for this study given the non-parametric nature of the data and the assumption of a monotonic relationship between the variables, that is the assumption that as training load increases the RPE values would also increase.

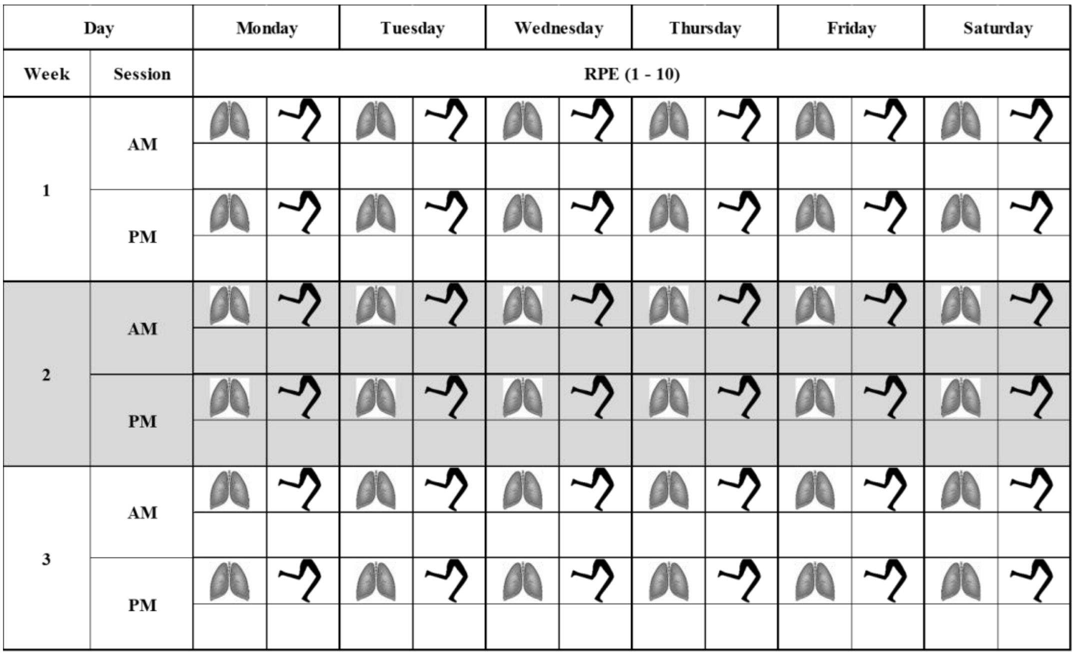
Table 15 - Shapiro-Wilk Test Results

	Division C	**Division B**
Duration (min)	<0.01 *Non-Normal Distribution*	<0.01 *Non-Normal Distribution*
Total Load (AU)	0.69 *Normal Distribution*	0.06 *Normal Distribution*
Vertical Load (AU)	0.33 *Normal Distribution*	<0.01 *Non-Normal Distribution*
Antero-Posterior Load (AU)	0.03 *Non-Normal Distribution*	0.03 *Non-Normal Distribution*
Medio-Lateral Load (AU)	0.10 *Normal Distribution*	<0.01 *Non-Normal Distribution*
RPE-L (AU)	<0.01 *Non-Normal Distribution*	<0.01 *Non-Normal Distribution*
RPE-B (AU)	<0.01 *Non-Normal Distribution*	<0.01 *Non-Normal Distribution*

Notes. Significance Level = 0.05, Outliers Included

4.4 Method

The participants for this study were 19 adolescent Badminton players (Age: 14.0 ± 0.8 y) based at a dedicated high performance youth training environment. With institutional ethical approval, each participant and parent/guardian was provided with a participant information sheet (see Appendix 4) and was required to complete an informed consent/assent form prior to the data collection. The athletes were assessed over a 4-week period within which they would train twice a day from Monday to Friday and once a day on Saturday. Only court-based training was assessed and gym-based training was excluded. Each athlete wore a VX Sport (Visuallex Sport International, Lower Hutt, New Zealand) log unit (dimensions: 74mm x 47mm x 17mm, weight: 50gm) between the scapulae in a purpose-built harness during each court-based training session for the duration of the data collection period. The VX Sport system has been found to possess both high intra-system and inter-system reliability with the Catapult Optimeye S5 system (see Study 1). However, to further limit any inter-unit reliability issues, the participants wore the same unit throughout the assessment period. After each training session the participants provided two ratings of perceived exertion (RPE) on a scale of 1 to 10, "RPE-L" being a measure of perceived biomechanical load at the legs and RPE-B being a rating for breathlessness and perceived overall physiological load (Weston *et al.*, 2015; McLaren *et al.*, 2016; McLaren *et al.*, 2018). Prior to the data collection the participants were briefed on the process and how to differentiate between the two RPEs, while pictures of lungs and legs were used in the record sheet to aide understanding, see Figure 12.



Day		Monday		Tuesday		Wednesday		Thursday		Friday		Saturday	
Week	Session	RPE (1 - 10)											
1	AM												
	PM												
2	AM												
	PM												
3	AM												
	PM												

Figure 12 - Differential RPE Record Sheet

After the completion of each training day, the accelerometer data was extracted at 100Hz using the accompanying VX Sport software. The raw data was filtered at 10Hz using a 3rd order Butterworth low pass filter and mean centred in Matlab (MathWorks, Natick, MA, USA). The data was mean centred to subtract any constants which may affect the interpretation of the data and to avoid the inflation of any one axis. The training load was calculated using a modified vector magnitude calculation, being the square root of the sum of activity counts squared (Boyd *et al.*, 2011) (Equation 4) and the load for the vertical, antero-posterior and medio-lateral axis were also calculated (Equation 5).

$$Training\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2 + (ay_1 - ay_{-1})^2 + (az_1 - az_{-1})^2}{100}}$$

Equation 4: Vector Magnitude Training Load

$$\text{Vertical Load} = \sqrt{\frac{(az_1 - az_{-1})^2}{100}} \qquad \text{Antero} - \text{Posterior Load} = \sqrt{\frac{(ay_1 - ay_{-1})^2}{100}} \qquad \text{Medio} - \text{Lateral Load} = \sqrt{\frac{(ax_1 - ax_{-1})^2}{100}}$$

Equation 5: Vertical, Antero, Medio Load calculations

To assess the sensitivity of the measures to differentiate between athletes of different age and playing experience, the athletes were split into two groups based on the chronological age bands used for local competitions, six athletes were in "Division C" (aged 12 to 14 years old) and 13 athletes were in "Division B" (aged 14 to 16 years old). The non-parametric Mann-Whitney U test was used to calculate the differences between groups, with significance set at ≤0.01 to accommodate for multiple testing.

To assess the correlation between the various RPE scores (total RPE, RPE-L and RPE-B) and training load measures, Spearman's Rank Correlation Coefficient was calculated. Interpretation of the Spearman's Rank Correlation Coefficient was based on the following descriptors (Schober *et al.*, 2018): 0.00-0.09 = "Negligible Correlation", 0.10-0.39 = "Weak Correlation", 0.40-0.69 = "Moderate Correlation", 0.70-0.89 = "Strong Correlation" and 0.90-1.00 = "Very Strong Correlation".

4.5 Results

The descriptive data from the training sessions are outlined in Table 16 and Figures 13 and 14. Significant differences were observed for total load, axis specific load (with higher loads for Division B athletes) and for both RPE measures (with higher RPE for Division C athletes).

Table 16 - Descriptive Training Load and Differential RPE by Age Group

Measure	**All Age Groups (n=218)** *Median (Range)*	**Division C (n=85)** *Median (Range)*	**Division B (n=133)** *Median (Range)*	***Division C vs. Division B*** *P Value*
Duration (min)	124 .00 (211.00)	125.00 (172.00)	123.00 (211.00)	0.48
Total Load (AU)	1711.50 (3738.71)	1494.80 (2846.11)	1833.40 (3485.14)	<0.001*
Vertical Load (AU)	977.24 (2559.72)	893.16 (1882.12)	1055.60 (2429.09)	<0.001*
Antero-Posterior Load (AU)	826.28 (2116.20)	670.96 (1870.20)	906.63 (1975.24)	<0.001*
Medio-Lateral Load (AU)	727.665 (2043.59)	651.46 (1011.59)	787.87 (1935.28)	<0.001*
RPE-L (AU)	7.00 (8.00)	7.00 (8.00)	7.00 (7.00)	<0.001*
RPE-B (AU)	7.00 (7.00)	7.00 (7.00)	6.00 (7.00)	<0.001*

* Significance of <0.01

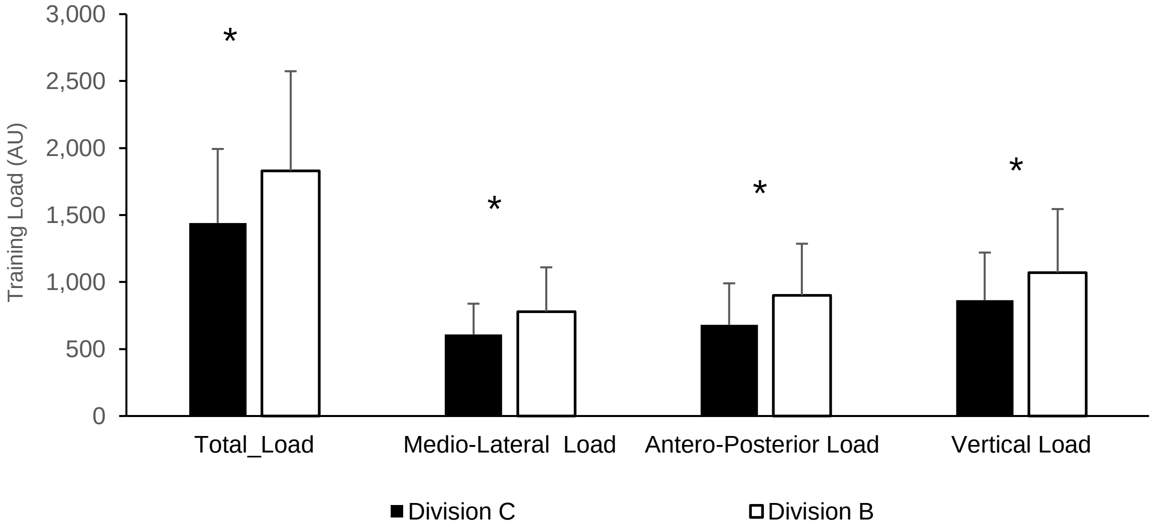


Figure 13 - Descriptive Training Load by Age Group *(* Denotes Significance of <0.01)*

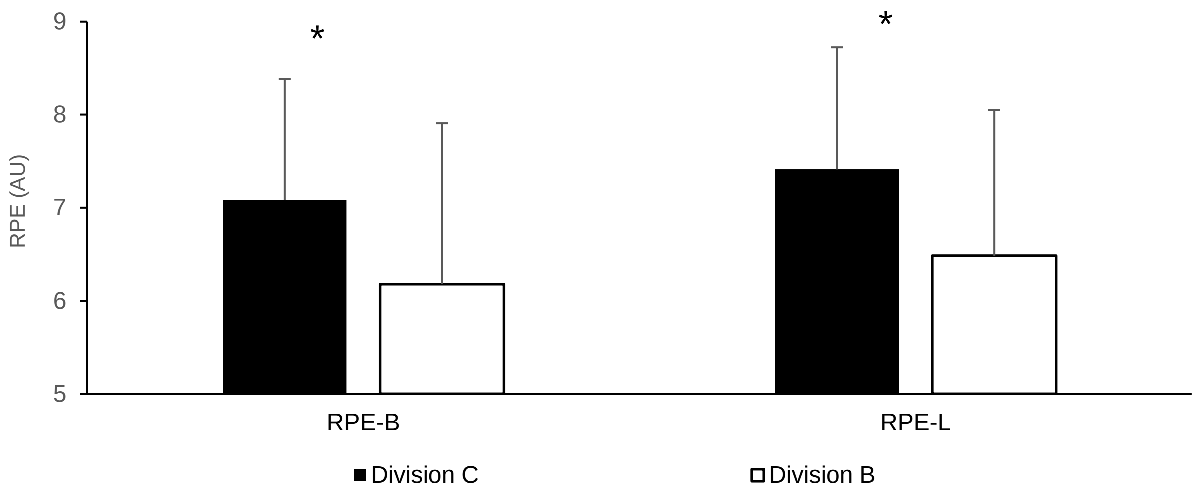


Figure 14 - Descriptive Differential RPE by Age Group *(* Denotes Significance of <0.01)*

The correlations between the training load and RPEs are outlined in Table 17. Overall, “negligible” and “weak” correlations were observed between the training load and the RPE values. The strongest correlation was observed between the vertical load and RPE-B values. Stronger correlations were observed when both the Division B and Division C athletes were viewed in isolation. For Division C the strongest correlation was observed between total load and RPE-L, while for Division B the strongest correlation was observed between the antero-posterior load and RPE-B.

Table 17 - Spearman's Rank Correlation Coefficient between Training Load and Differential RPEs

	Total Load	**Vertical Load**	**Antero-Posterior Load**	**Medio-Lateral Load**
All Age Groups (n=218)				
RPE-L	r_s = 0.073 *Negligible Correlation*	r_s = 0.074 *Negligible Correlation*	r_s = 0.042 *Negligible Correlation*	r_s = 0.074 *Negligible Correlation*
RPE-B	r_s = 0.128 *Weak Correlation*	r_s = 0.134* *Weak Correlation*	r_s = 0.110 *Weak Correlation*	r_s = 0.056 *Negligible Correlation*

Division C (n=85)				
RPE-L	r_s = 0.204 *Weak Correlation*	r_s = 0.193 *Weak Correlation*	r_s = 0.149 *Weak Correlation*	r_s = 0.155 *Weak Correlation*
RPE-B	r_s = 0.099 *Negligible Correlation*	r_s = 0.108 *Weak Correlation*	r_s = 0.072 *Negligible Correlation*	r_s = 0.030 *Negligible Correlation*
Division B (n=133)				
RPE-L	r_s = 0.167 *Weak Correlation*	r_s = 0.142 *Weak Correlation*	r_s = 0.161 *Weak Correlation*	r_s = 0.110 *Weak Correlation*
RPE-B	r_s = 0.277* *Weak Correlation*	r_s = 0.251* *Weak Correlation*	r_s = 0.280* *Weak Correlation*	r_s = 0.219* *Weak Correlation*

* Significant

4.6 Discussion

The purpose of this study was (1) to assess the use of upper trunk-mounted IMUs to differentiate training load based on age group and (2) to ascertain if axis specific training load provide an improved method of quantifying lower limb biomechanical loading compared to total training load.

Significant differences were observed between the two age groups, with Division B athletes (14 to 16 years old) demonstrating higher total load and axis specific loads, coupled with lower RPE scores for both overall breathlessness and specified to the lower limbs than Division C athletes (12 to 14 years old). The increase in training load is consistent with studies of adolescents' populations within other sports. For example, significant differences in running distance and high-speed running distance were observed in adolescent Australian Rules Football players, with higher distances recorded for the older age groups (Gastin *et al.*, 2017). These differences can be attributed to the underlying physical qualities, such as agility, speed, power and strength which develop during adolescents and enable older athletes to withstand higher loads (Lloyd and Oliver, 2012). In the study of Australian Rules Football players, 20m Sprint Performance, Maximal Speed of 20m, Vertical Jump Height and Multistage Fitness Test scores also demonstrated significant differences based on the age of the athletes (Gastin *et al.*, 2017).

The significantly higher RPEs recorded within the younger age group is also consistent with findings in the literature. In a study of adolescent Swimmers, it was found that the younger age groups (11-12 years old and 13-14 years old) recorded higher RPEs than the expected ratings given by the coach for “easy” and “moderate” sessions (Barroso *et al.*, 2014). However, for the older age group (15-16 years old) there were no significant differences between the athletes and coach perceptions for “easy” and “moderate” sessions. All age groups reported lower RPEs compared to the coaches’ ratings for the “difficult” sessions. The authors concluded that more experienced athletes could perceive effort better than less experienced athletes due to greater variability (e.g., anaerobic, aerobic) along the years of training (Barroso *et al.*, 2014), which also provides a potential explanation for the differences observed between the two Badminton age groups.

Overall “negligible” to “weak” correlations were observed between the training load and differential RPE values. These weak correlations are consistent with the findings from the study of Australian Rules Football, where “trivial”, “small” or “unclear” differences were observed between the Player Load and Player Load (2D) values and the differential RPEs (Weston *et al.*, 2015). RPE-B, which represented the participants’ perceived breathlessness, had slightly higher correlations to total load and axis specific load compared to RPE-L, however all correlations were “negligible” or “weak”.

Contrary to the hypothesis of this study, vertical load was more strongly correlated with the RPE-B and not RPE-L, but again these correlations were both “negligible” or “weak”.

While session RPE has been shown to be a valid form of quantifying training load in youth athletes (Haddad *et al.*, 2011; Padulo *et al.*, 2014), it has been observed that youth athletes with greater training experience are able to more accurately perceive exertion compared to youth athletes with less experience (Barroso *et al.*, 2014). With this context, the older group (Division B), with a longer training history, may provide more reliable RPEs compared to the younger and less experienced group (Division C). In this study, Division B demonstrated a stronger correlation between total load and RPE-B, while in contrast Division C recorded stronger correlations between total load and RPE-L. Division C was the only instance where the stronger correlation was observed between vertical load and the RPE-L compared to RPE-B, but this correlation remained “weak”.

While the use of RPE to quantify training load has been validated in Tennis (Gomes *et al.*, 2015), a study of elite junior Tennis players highlighted the complexity of load perception (Murphy and Reid, 2013). In this study, the session RPE and drill RPE from junior Tennis players during training were compared to the expected session RPE and drill RPE as rated by their coaches. While there were high levels of agreement between actual and expected drill RPE, there were significant differences between the actual and expected session RPE. This study highlighted that for junior Tennis players the total session RPE is greater than the sum of the RPE of the individual drills. In a Badminton context, explosive lower limb movements observed during training (jumps, lunges etc.) would create high accelerometer derived vertical load and high RPE-L. By contrast, holding a low position (isometric squat) while waiting for an opponent's shot, would produce low accelerometer derived vertical load but potentially high antero-posterior load and RPE-L values. These "low load, high RPE" movements may explain the difference between the vertical load and RPE-L values found in the current study, as the total lower limb exertion of the session (RPE-L) is greater than the sum of the explosive lower limb movements (vertical load) within the session.

The reporting of loads from the individual axis is currently not commonplace and the results from this study suggest that this approach may not provide any greater resolution to differentiate between lower limb and other types of loading for youth Badminton players. In Badminton match play, the lunge accounts for 15% of movements and produces high forces experienced in the lower limbs (Kuntze *et al.*, 2009). Youth athletes have been shown to be inefficient in using impact forces of the lunging movement in racket sports (Williams and Kuitunen, 2010), emphasising the importance of understanding the loading associated with this movement. In a lunging movement the upper trunk does not remain upright meaning that the vertical axis of the IMU, when placed between the scapulae, is no longer aligned to the direction of the vertical force, see <u>Figure 15</u>. This misalignment between the vertical axis of the IMU and the direction of the vertical force during movements that are major causes of lower limb loading, such as the lunge, may be a factor in poor correlation between vertical load and RPE-L in this study.

Figure 15 – Example of a Badminton Lunge Movement

In addition to the orientation of the IMU, the placement of the IMU on the upper back is another potential source of error in assessing lower limb loading. While both upper and lower back IMU placement are common in many team and individual sports, there are potential issues in the ability to accurately measure athlete loading, especially in the lower limbs. In a study of Rugby Union players, it was found that upper trunk-mounted IMUs exhibited poor reliability and were non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). The authors suggested that the elasticised harness of the IMU was one of the major contributors to extraneous accelerometer magnitudes. The high degree of error may also be due to the IMU being positioned far from the point of ground contact, therefore mechanical energy is absorbed and dissipated through the joints and trunk tissues between the foot and the IMU (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b).

Given the limitations of upper trunk-mounted IMUs for assessing lower limb loading, a more direct measure may be required to monitor lower limb loading. It has been demonstrated that lower limb-mounted IMUs were able to quantify loads more directly than those mounted on the upper trunk and measure asymmetry of running in Rugby League players (Glassbrook *et al.*, 2020a; Glassbrook *et al.*, 2020b). Tibia-mounted IMUs have been found to provide good to excellent reliability for measurement of impact loading during Football (Soccer) specific acceleration-deceleration, plant and cut and change of direction tasks (Burland *et al.*, 2021). Lower limb-mounted IMUs have also been able to differentiate between athletes with and without lower back pain during Cricket fast bowling (Senington *et al.*, 2020).

Lower limb-mounted IMUs may therefore provide a more direct measure of lower limb loading and assessment of movement asymmetry in Badminton, which may have potential implications for injury management. Given the potential benefits of using lower limb-mounted IMUs for the management of injury risk and movement asymmetries, further study is warranted to assess the application of this technology within Badminton.

4.7 Conclusion

This study sought to (1) assess the use of upper trunk-mounted IMUs to differentiate training load based on age group and (2) ascertain if axis specific training load provides a more precise method of quantifying lower limb loading compared to total training load. Significantly higher training loads and lower RPE values were recorded in the older age group compared to the younger age group. These differences can be attributed to the underlying physical qualities, such as agility, speed, power and strength, which develop during adolescents and enable older athletes to withstand higher loads.

Overall “negligible” to “weak” correlations were observed between the training load and RPE values. The training load for the vertical axis showed a stronger correlation with RPE-B than RPE-L. When the population was split based on chorological age and playing experience, vertical load for those older athletes was also more strongly correlated to the RPE-B. The lack of correlations found in this study can be attributed to “low load, high RPE” movements (such as the isometric squat) that are not captured through accelerometer derived training load, the vertical axis of the IMU not being aligned to the direction of the vertical load during key movements, such as lunges, and the positioning of the IMU on the upper back which is located away from the point of ground contact, resulting in mechanical energy being absorbed and dissipated.

The results from this study suggest that axis specific training load from the vertical axis does not provide greater insight into lower limb biomechanical loading compared to overall training load in adolescent Badminton players and that other methods for isolating lower limb loading are required. Lower limb-mounted IMUs have been found to be a valid tool for measuring lower limb loading in field-based sports and have potential applications in Badminton that warrant further investigation.

4.8 Future Study

Study 2 has demonstrated that accelerometer derived training load from a single upper trunk-mounted IMU is poorly correlated to both overall and lower limb specific RPEs in adolescent Badminton players. Axis specific training loads also demonstrated poor correlations with both RPEs. It is therefore likely that additional IMUs, specifically placed directly on the lower limbs, as has been utilised in several field-based sports (Glassbrook *et al.*, 2020a; Glassbrook *et al.*, 2020b; Senington *et al.*, 2020; Burland *et al.*, 2021), may provide a more direct measure of the lower limb loading in Badminton players. Lower limb-mounted IMUs also have the added benefit of allowing for the assessment of lower limb asymmetry, which has been linked to injury prevalence, and performance detriment in racket sport athletes (Madruga-Parera *et al.*, 2020).

However, while the use of multiple IMUs, upper trunk-mounted and lower limb-mounted, may be required to more accurately assess loading in Badminton players, a potential limitation is that coaches may be reluctant to allow their athletes to wear multiple IMUs during training and competition. In a study of National Collegiate Athletic Association (NCAA) and professional sport coaches, 73% reported frustrations with wearable technologies due to inaccurate data, lack of meaningful recommendations and challenges in getting the technology to work consistently. Respondents also highlighted that athletes were reluctant to use wearable technologies due to the perceived lack of comfort, inconvenience, appearance and concerns that they are being tracked. To quote one coach, “wearables are fool’s gold” (Luczak *et al.*, 2020).

As collaboration between sport scientists and coaches is instrumental for the success of performance analysis systems (Hughes and Bartlett, 2002), a nuanced and symbiotic relationship between the sport scientist and the coach is required when planning data collection and developing performance analysis outputs (Bampouras *et al.*, 2012). It is therefore important to consider the perception of coaches towards the specific technology when assessing the potential use of multiple IMUs for performance analysis and/or load monitoring. Study 3 will therefore seek to understand the perceptions of racket sports coaches towards the use of IMUs in training and competition.

An update to the research questions and proposed study titles and study design with the key findings from Studies 1 and 2 are outlined in Table 18.

Table 18 - Proposed Research Questions, Study Titles, Study Design and Key Findings

Research Questions	**Study Title**	**Study Design**	**Key Findings**
Are commercially available IMUs a reliable and valid tool for quantifying Badminton specific movements?	**Study 1:** Intra- and inter-system reliability of upper body-mounted Inertial Measurement Units for the measurement of Badminton specific training load	Reliability Study	1. Different commercially available IMUs are reliable to compare Badminton specific movements. 2. Higher levels of reliability are achieved when the same IMU system is used.
Does axis specific accelerometer derived training load from an upper body-mounted IMU accurately quantify lower limb biomechanical load in Badminton players?	**Study 2:** Axis specific training load to quantify lower limb biomechanical loading in adolescent Badminton players	Correlational Study	1. Training load obtained from a single upper trunk-mounted IMU is poorly correlated to both overall RPE and lower limb specific RPE in adolescent Badminton players. 2. Axis specific training load from the vertical axis does not provide greater insight into

			lower limb biomechanical loading.
What are coaches perceptions towards the use of IMUs in racket sports during training and competition?	**Study 3:** Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition	Quantitative Survey	
Can limb specific load and asymmetry measurements from tibia-mounted IMUs discriminate between athletes with and without unilateral or bilateral lower limb injury history?	**Study 4:** Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history	Cross Sectional Observational Study	

Chapter 5: Study Three

5.1 Study Three: Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition

5.1.1 Research Question

What are coaches' perceptions towards the use of IMUs in racket sports during training and competition?

Parts of this study have been published in:

Wylde, M.J., Masismadi, N.A., Low, C.Y., Callaway, A.J. and Williams, J.M. 2021. Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition. *International Journal of Racket Sports Science,* 3(1), 45-55 (see Appendix 5).

5.2 Introduction

Study 2 demonstrated that accelerometer derived training load from a single upper trunk-mounted IMU is poorly correlated to both overall and lower-limb specific RPEs in adolescent Badminton players. Axis specific training loads also demonstrated poor correlations with both RPEs.

This is consistent with a study of Rugby Union players, where upper trunk-mounted IMUs have been shown to exhibit poor reliability and were found to be non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). As upper body-mounted IMUs are positioned further away from the point of ground contact, the impact forces are dissipated through the joints and body tissues between the foot and the IMU, resulting in a loss of validity (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b).

In Badminton, training load and relative distance derived from an upper trunk-mounted IMU were only correlated to the heart-rate measures at the High Intensity zone and not at the Low or Medium Intensity zones, with the latter showing a negative correlation in both cases (Abdullahi *et al.*, 2019). The overall high work density observed in Badminton compared to field-based sports makes it difficult to observe clear differences in the Low and Medium Intensity zones. Therefore, the consideration as to whether the upper body is the ideal location for IMU placement depends on a critical understanding of what information can be obtained from a specific sensor location.

IMUs worn directly on the lower limb (tibia) and shoes have been utilised in Rugby League to measure accelerations during sprinting (Glassbrook *et al.*, 2020a) and to assess lower limb asymmetry (Glassbrook *et al.*, 2020b). IMUs worn on the lower limbs are therefore able to measure forces more directly than units mounted on the upper body (Glassbrook *et al.*, 2020a). This provides practitioners with a more precise method for measuring lower limb loading, which can facilitate the improved prescription and management of training load. Tibia mounted IMUs have also been found to provide good to excellent reliability for measurement of impact loading and step count during Football (Soccer) specific acceleration-deceleration, plant and cut and change of direction tasks (Burland *et al.*, 2021). In addition, in a study of Cricket fast bowlers, time to peak tibial accelerations during the front foot impact differentiated between athletes with and without lower back pain (Senington *et al.*, 2020).

Lower limb-mounted IMUs may therefore provide a more direct measure of the forces and loads acting on the lower limbs in racket sports, which may have potential implications for injury management. In studies of elite Badminton players, lower limb injuries have accounted for between 43% (Yung *et al.*, 2007) and 54% (Guermont *et al.*, 2021) of all injuries sustained. In a separate study, 64% of injuries recorded in youth Badminton players were soft-tissue sprains and strains with knee injuries being the most common, accounting for 42% of injuries to the lower limbs (Goh *et al.*, 2013). Therefore, monitoring specific anatomical regions of the body during sports like Badminton may offer anatomically focussed force and load information which could hold insights into injury prediction and rehabilitation targets.

Whilst sensor placement will be important and related to the area under investigation, the use of multiple IMUs could allow for some redundancy in the data collection. However, a potential limitation to the concurrent use of multiple IMUs is that coaches may be reluctant to allow their athletes to wear IMUs during training and competition. As collaboration between sport scientists and coaches is instrumental for the success of performance analysis systems (Hughes and Bartlett, 2002), a close working relationship and common understanding between the sport scientist and the coach is required when planning data collection and developing performance analysis outputs (Bampouras *et al.*, 2012). It is therefore important to consider the perception of coaches towards the specific technology when assessing the potential use of multiple IMUs for performance analysis and/or load monitoring.

To date there is a lack of research pertaining to the acceptance by coaches towards the use of wearable technology. In one of the few published studies in this area, 113 strength and conditioning (S&C) coaches and athletic trainers (AT) working within the National Collegiate Athletic Association (NCAA) and professional sport were surveyed on their opinions towards the use of wearable technologies (Luczak *et al.*, 2020). In the pilot study of 25 S&C coaches and ATs, it was found that 76% reported a negative response to the use of wearable technologies, sighting that wearables were not measuring what the practitioners needed and highlighting a significant lack of trust with existing wearables solutions. In the full study of 113 S&C coaches and ATs, 73% reported frustrations with wearable technologies due to inaccurate data, lack of meaningful recommendations and challenges in getting the technology to work consistently. Respondents also highlighted that athletes were reluctant to use wearable technologies due to the perceived lack of comfort, inconvenience, appearance and concerns that they are being tracked. To quote one coach, "wearables are fool's gold" (Luczak *et al.*, 2020). This study highlighted that regardless of the reliability and validity of wearable technologies, a lack of coach acceptance can negatively impact the use and adherence from athletes. Furthermore, this study was with a group of S&C coaches and ATs, who are potentially more accustomed to the use of wearable technology, meaning that the concerns raised could be amplified further when applied to sport specific coaches.

Given the limitation of single upper trunk-mounted IMUs for assessing lower limb loading, the potential benefits of lower limb-mounted IMUs and the potential reluctance of coaches to allow the use of multiple IMUs, this study seeks to understand the perceptions of racket sport coaches towards the use of IMUs in training and competition.

5.3 Justification of Method

To understand the preferences of coaches towards the use of IMUs during training and competition, a qualitative research method is required. When setting up qualitative research projects there are a number of factors which require consideration. Online surveys are useful when seeking to approach a large number of participants as minimum contact time with the participants is required, while focus groups and interviews are conducted within a smaller number of participants and provide the opportunity for different avenues of inquiry to be explored (Harper and McCunn, 2017). As the purpose of this study is to obtain responses from a comparatively large group of coaches for a number of fixed questions, an online survey is assessed to be the most appropriate method.

Responses to blind surveys of coaches have been found to be low, for example 24.2% in a study of youth Football (Soccer) coaches (Mawson *et al.*, 2018). The primary reasons for non-response to online surveys have been found to be survey burden and a lack of time to complete the survey (Cunningham *et al.*, 2015). In the design of an online survey, it is important to consider the number of questions and thus the time required to complete the survey (Harper and McCunn, 2017). The survey was therefore designed to be as a quick to complete as possible to maximise potential respondents, with primarily multiple-choice questions and minimal open-ended/free text questions.

Factors such as layout, aesthetics and language used should also be considered during the creation of an online survey (Harper and McCunn, 2017). To this end, the language used within the survey was kept as simple as reasonably possible and the use of pictures was incorporated to demonstrate the position of the IMU to avoid confusion (see Figure 16). In addition, as three of the most prominent Badminton, Squash and Table Tennis playing nations are China, Malaysia and Indonesia, the survey was translated into Mandarin and Bahasa to reach out to as many coaches as possible, who may not be able to respond to the survey in English.

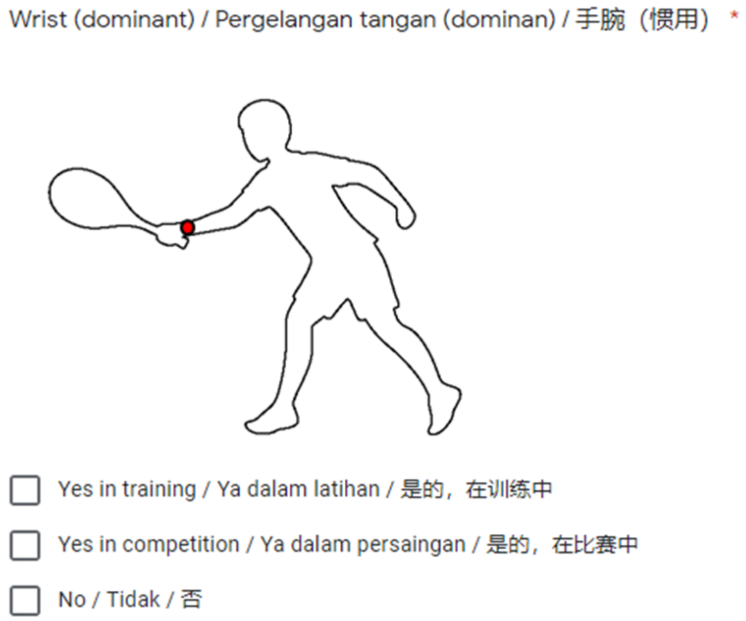


Figure 16 - Example of Language, Layout and Aesthetics of the Online Survey

In addition to the general preference of coaches towards the use of IMUs during training and competition, an important purpose of the survey was to ascertain which IMU placement the coaches would be most accepting towards. During the literature review a number of IMU placements which are commonly used in racket sports were outlined (see Table 19), which were included in the survey. In addition, given the use of lower limb and shoe-mounted IMUs within field-based sports (Glassbrook *et al.*, 2020a; Glassbrook *et al.*, 2020b; Senington *et al.*, 2020; Burland *et al.*, 2021), and the potential benefits of these placements in racket sports, the option for lower limb and shoe IMU placement was also included within the survey.

Table 19 - Placement of IMU in Racket Sports

Sport	**Wrist**	**Lower Leg**	**Hand**	**Lower Arm**	**Upper Arm**	**Racket Handle**	**Racket Head**	**Upper Back**	**Lower Back**	**Reference**
Badminton								*		Abdullahi *et al.*, 2019
Badminton							*			Anik *et al.*, 2016
Badminton							*			Chang *et al.*, 2009
Badminton			*	*	*	*				Chew, Su *et al.*, 2015
Badminton	*				*					Chew, Sim *et al.*, 2015
Badminton									*	Dieu *et al.*, 2014
Badminton				*						Jacob *et al.*, 2016
Badminton							*			Koon *et al.*, 2005
Badminton				*						Raina *et al.*, 2017
Badminton	*		*	*	*					Rusydi *et al.*, 2015
Badminton								*		Sasaki *et al.*, 2018
Badminton	*				*	*				Steels *et al.*, 2020
Badminton	*									Taha *et al.*, 2016
Badminton	*	*								Wang *et al.*, 2016
Badminton						*				Yu and Zhao, 2013
Table Tennis						*				Blank *et al.*, 2015

Table Tennis				*		Boyer *et al.*, 2013
Table Tennis	*					Guo *et al.*, 2010
Tennis	*		*			Ahmadi *et al.*, 2009
Tennis		*				Connaghan *et al.*, 2011
Tennis					*	Gale-Ansodi *et al.*, 2017
Tennis	*					Kos *et al.*, 2016
Tennis	*					Whiteside *et al.*, 2017
Tennis & Badminton	*					Anand et al 2017

Quantitative surveys of coaches' perceptions have been published with a sample of 46 respondents (Wright *et al.*, 2012). Therefore, a desired minimal sample size of 46 respondents was set for this study. Given the general low response rates from coach to online surveys (Mawson *et al.*, 2018), a larger pool of 140 coaches were contacted and a response window was set at 6 months.

As the responses collected from the survey would be nominal in nature, the Chi Square test was deemed to be the most appropriate. The Chi Square Goodness of Fit test is used to compare the distribution of cases among values of a categorical variable with a theoretically expected distribution and is distinct from the Chi Square Test of Independence, which is used in the comparison of two categorical variables (O'Donoghue, 2012). For this study one categorical variable is being assessed, this being whether the surveyed coaches would allow their athletes to use the IMUs at various positions during either training or competition. The theoretically expected distribution was that 50% of coaches would be supportive and 50% of coaches would not be supportive. The Chi Square Goodness of Fit test was therefore deemed to be the most appropriate test and has been selected for use in this study.

5.4 Methods

A sample of racket sport coaches was approached to complete an online survey relating to their perception of the use of IMUs in training and competition. Participants selected were those who indicated their primary job role (source of income) as a coach in either Badminton, Squash, Table Tennis or Tennis in their profile on the professional networking platform LinkedIn (LinkedIn Corporation, Mountain View, California, USA).

A total of 140 coaches were contacted to complete the survey of which 41.4% (58) responded. Of the respondents, 44.8% (26) were Badminton coaches, 27.6% (16) were Table Tennis coaches, 18.9% (11) were Squash coaches, and 8.6% (5) were Tennis coaches. Of the respondents, 55.2% (32) classified themselves as coaching at an elite level, while 44.8% (26) classified themselves as coaching at a sub-elite level (either school, club or youth development). The respondents were from a total of 19 countries with Singapore (32.8%; 19) and the United Kingdom (13.8%; 8) having the highest number of respondents.

The purpose of the survey was to ascertain the coaches' perspectives on the use of IMUs in training and competition. The key themes of the questions were as follows, with the full survey outlined in Appendix 6.

Demographic information: Participants were asked which sport they coached, the level at which they coached (elite, youth, club or school) and the country in which they resided.

Use of IMUs: IMU shape, size and use were described and participants were asked if they would allow their athletes to wear IMUs in training and/or competition and, if yes, how many units they would allow their athletes to wear in training and competition respectively.

Placement of IMUs: Participants were asked if they would allow their athletes to wear IMUs at various locations on the body during training and/or competition. The suggested placements of the IMUs were based on the current literature, as highlighted in Table 17, with the addition of placement on the lower limbs and shoes (Glassbrook *et al.*, 2020a; Glassbrook *et al.*, 2020b; Senington *et al.*, 2020; Burland *et al.*, 2021), given the potential benefit of these approaches in a racket sport context.

The anonymous online survey was created via Google Forms (Google LLC, Mountain View, California, USA). The responses were downloaded as a Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) file and exported into R (The R Foundation, Vienna, Austria) for processing and analysis. Given the categorical nature of the data, *p*-values were calculated using the Chi Square Goodness of Fit test with alpha set at 0.05.

5.5 Results

Of the 58 racket sports coaches who completed the survey, a significant proportion, 96.6% (56), indicated that they would allow their athletes to wear IMUs in training (see

Table 20). Overall, the median number of units that the coaches would allow their athletes to wear during training was two (see Figure 17). Of the coaches who responded, 65.5% (38 out of 58) would allow their athletes to wear IMUs during competition. The median number of units that the coaches would allow their athletes to wear during competition was one.

Table 20 - Racket Sport Coaches Responses to the Use of IMUs and Number of Units in Training and Competition *(* Denotes significance of p<0.05)*

Training				Competition			
No	**Yes**	***P*-value**	**Median**	**No**	**Yes**	***P*-value**	**Median**
2	**56**	<0.001*	2	20	**38**	0.013	1

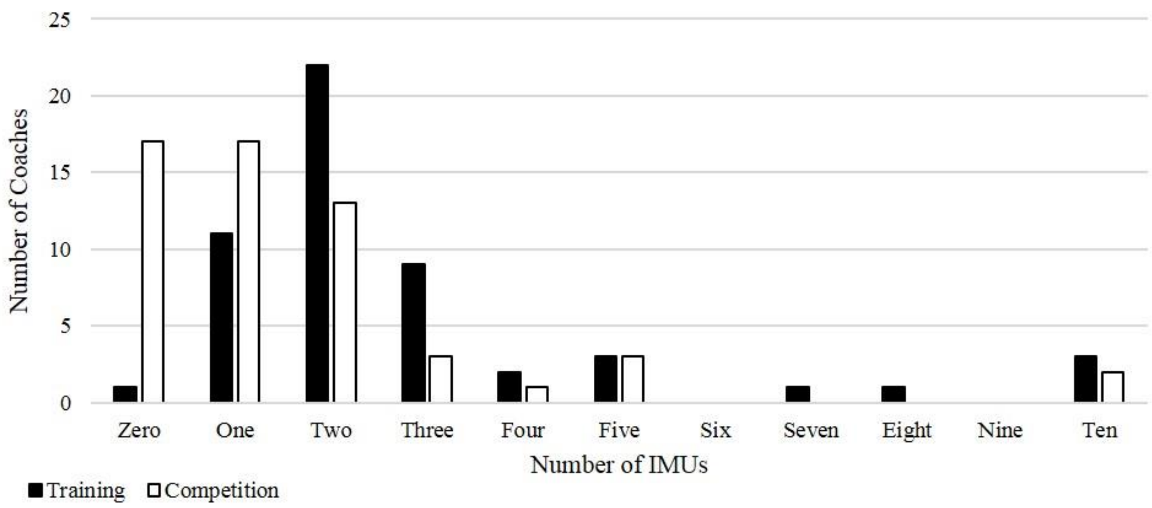


Figure 17 - Maximum Number of IMUs Supported for Use During Training and Competition (Excluding Outliers Above 10 Units)

For use in training, coaches were significantly more likely to agree to their athletes wearing IMUs positioned on the Upper Back, Lower Back, Dominant Wrist, Non-Dominant Wrist, Non-Dominant Lower Arm, Dominant Upper Arm, Lower Leg and Shoe (see Table 19). By contrast, for use in competition, coaches were significantly less likely to agree to their athletes wearing IMUs positioned on the Lower Back, Dominant Wrist, Dominant Hand, Non-Dominant Hand, Dominant Lower Arm, Non-Dominant Lower Arm, Dominant Upper Arm, Lower Leg, Racket Handle and Racket Head.

Table 21 - Racket Sport Coaches Responses to the Use of IMUs at Various Body and Equipment Positions in Training and Competition *(* Denotes significance of p<0.05)*

		Training			Competition	
Placement	**No**	**Yes**	***P*-Value**	**No**	**Yes**	***P*-Value**
Upper Back	10	**48**	<0.001*	35	23	0.107
Lower Back	15	**43**	<0.001*	**43**	15	<0.001*
Dominant Wrist	17	**41**	0.001*	**44**	14	<0.001*
Non-Dominant Wrist	10	**48**	<0.001*	28	30	0.793
Dominant Hand	29	29	1.000	**51**	7	<0.001*

Non-Dominant Hand	25	33	0.289	**43**	15	<0.001*
Dominant Lower Arm	23	35	0.107	**48**	10	<0.001*
Non-Dominant Lower Arm	16	**42**	<0.001*	**42**	16	<0.001*
Dominant Upper Arm	21	**37**	0.029*	**49**	9	<0.001*
Non-Dominant Upper Arm	19	**39**	0.005*	**43**	15	<0.001*
Lower Leg	12	**46**	<0.001*	**43**	15	<0.001*
Shoe	11	**47**	<0.001*	36	22	0.058
Racket Handle	25	33	0.289	**48**	10	<0.001*
Racket Head	31	27	0.599	**49**	9	<0.001*

5.6 Discussion

Despite the majority of coaches who responded to the survey (65.5%) indicating that they would allow their athletes to wear IMUs during competition, this was not reflected in the responses regarding the positioning of the IMUs. In fact, only Non-Dominant Wrist showed an overall positive response (51.7%), while 11 of the proposed positions demonstrated significant negative responses from the coaches. While the coaches may have understood the benefits of data collected from wearable IMUs during competition, such as the ability to provide real-time feedback and reduced labour-intensiveness compared to video analysis (Chambers *et al.*, 2015), when it came to considering the placement of IMUs at specific locations, concerns regarding inconvenience to the athlete, lack of comfort, and appearance may have become more apparent (Luczak *et al.*, 2020). While this trade-off may have been deemed acceptable during training, it is clear that in competition, the majority of racket sport coaches were uncomfortable with allowing their athletes to use IMUs.

In a study of elite coaches' perspectives towards the use of technology, a number of potential challenges to the implementation of technology were identified (Jaswal, 2020). This included lack of athlete acceptance (36%), lack of support/acceptance from other coaches (27%) and concerns around losing subjectivity given an over-reliance on technology (27%). It is likely that these factors had an influence on the racket sport coaches' acceptance of the use of wearable IMUs during competition. For example, the perceived reluctance of an athlete to use the IMUs during competition may reduce the coaches' desire to adopt the technology. In the same study, the need to witness the concrete benefits and impact of technology was highlighted as a major factor in the coaches' decision to adopt a technology (Jaswal, 2020). While the surveyed racket sport coaches in the current study were informed that "the use of sensors can provide insights on the technical and tactical ability of the athletes", the lack of concrete evidence may have influenced the coaches' acceptance of the technology in the perceived higher-stakes competition environments. There is a perceived risk of wearing IMUs during competition, particularly as athletes may blame the technology for a poor performance (Luczak *et al.*, 2020). Coaches would therefore require significant evidence regarding the benefits of the technology on performance, recovery or injury management before accepting this perceived risk during competition (Jaswal, 2020). Future studies are required to explore to what extent the adoption of wearable technology impacts performance, thus providing insights from which coaches and athletes can base these decisions.

A model of the five stages in the innovation-decision process (Rogers, 2003) highlights knowledge and persuasion as being the first two stages towards the decision to adopt a new innovation. Within the persuasion stage, relative advantage, compatibility, complexity, trial-ability and observability were highlighted as perceived characteristics of innovation. When applied to the innovation-decision process in a sport context, these factors may need to be addressed to persuade coaches to adopt new technologies. For example, an explanation of the potential advantages of the wearable IMUs, coupled with a trial of the technology may have resulted in a high acceptance of use during competition. Giblin, Tor and Parrington (2016) outlined a number of trade-offs between the adoption of consumer-grade or "gold standard" sport technologies that included cost, expertise required to use the technology, and ease of which coaches and/or athletes can understand the data. These trade-offs also highlight key considerations which should be addressed within the persuasion stage when practitioners engage coaches regarding the adoption of new technologies.

While there was limited support from the surveyed racket sport coaches for the use of IMUs in competition, the use of IMUs in a variety of positions during training had significant positive responses. The general support for the use of IMUs during training, 96.6% of respondents, was in contrast to the limited current literature, where only 24% of respondents reported a positive experience of wearable technologies (Luczak *et al.*, 2020). The use of IMUs on the Non-Dominant Wrist and Dominant Wrist had significant positive responses. Wrist-worn IMUs have been found to be a reliable and valid method for stroke recognition and the assessment of movement within a controlled setting with Badminton (Chew *et al.*, 2015; Rusydi *et al.*, 2015; Taha *et al.*, 2016; Wang *et al.*, 2016; Anand *et al.*, 2017), Table Tennis (Guo *et al.*, 2010) and Tennis (Ahmadi *et al.*, 2009; Kos *et al.*, 2016; Anand *et al.*, 2017; Whiteside *et al.*, 2017). As wearable IMUs become smaller and less intrusive, and given the coaches' support for the use of IMUs in this position, it is likely that the use of IMUs on the wrist can become part of regular monitoring in racket sports.

The use of IMUs worn on the Upper Back and Lower Back in training also had significant positive responses. The use of the IMUs worn on the upper back is common across a range of sports (Chambers *et al.*, 2015) and has been used to assess training load in racket sports (Dieu *et al.*, 2014; Gale-Ansodi *et al.*, 2017; Sasaki *et al.*, 2018; Abdullahi *et al.*, 2019). However, the findings from Study 2 demonstrated a low correlation between loading data obtained from an upper trunk-mounted IMU and differential RPE at the lower limbs. This questions the validity of upper trunk worn IMUs for the measurement of playing intensity in Badminton. It has been demonstrated that upper trunk-mounted IMUs have limited reliability when assessing lower limb forces and loads due to the impact forces being dissipated through the joints and body tissues between the foot and the IMU (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b). A more direct measure of athlete loading may therefore be required for racket sport athletes.

The use of IMUs worn at the Lower Leg and Shoes in training had significant positive responses. Given the high prevalence of lower limb injuries in racket sports (Yung *et al.*, 2007; Shariff *et al.*, 2009; Goh *et al.*, 2013; Guermont *et al.*, 2021), the use of lower limb-mounted IMUs may provide a more direct measure of lower limb loading in racket sport athletes. In field-based sports, lower limb-mounted IMUs have been used to measure accelerations (Glassbrook *et al.*, 2020a), impact loading and step counts (Burland *et al.*, 2021), assess lower limb asymmetry (Glassbrook *et al.*, 2020b) and differentiate between athletes with and without pain (Senington *et al.*, 2020). Given that coaches support the use of IMUs worn at the Lower Leg and Shoes in training, a similar approach warrants further investigation as a method for assessing lower limb loading in racket sport athletes.

Overall, despite the evidence demonstrating the reliability and validity of wearable technologies, the lack of acceptance from coaches may negatively affect the use of these technologies and the adherence of athletes. It is therefore suggested that practitioners put emphasis on understanding the perceptions of coaches towards the use of wearable technologies, as has been attempted in this study, and seek to address concerns that coaches have in order to enhance the desired symbiotic relationship between sport scientist and coach.

5.7 Conclusion

This study sought to assess the perception of racket sport coaches towards the use of IMUs during training and competition. It was found that racket sport coaches were supportive of the use of IMUs during training. While coaches also indicated support for the use of IMUs during competition, no IMU placement was found to have a significantly positive response. This suggests that while coaches understand the benefits of collecting data from IMUs during competition, there remains concerns regarding inconvenience to the athlete, lack of comfort, and appearance.

For use in training, IMUs positioned at the Upper Back, Lower Back, Dominant Wrist, Non-Dominant Wrist, Non-Dominant Lower Arm, Dominant Upper Arm, Lower Leg and Shoe had significant positive responses. Wrist-worn IMUs have been used for shot detection and movement assessment, and have the potential to be used as a regular monitoring tool during training. While upper and lower trunk-mounted IMUs are commonplace across a range of sports, the distance between the IMU and the foot-ground contact means that the position may not be suitable for the assessment of lower limb loading. As the use of IMUs positioned at the Lower Leg and Shoe had positive responses from racket sport coaches, the use of lower limb-mounted IMUs for load monitoring in racket sports warrants further investigation.

Future Study

Study 3 has demonstrated that racket sport coaches are supportive of the use of IMUs during training, although not in competition. As Upper Back, Lower Back, Dominant Wrist, Non-Dominant Wrist, Non-Dominant Lower Arm, Dominant Upper Arm, Lower Leg and Shoe all received significantly positive responses from coaches, it is justifiable to use these placements for the assessment of racket sport athletes. Specific to Badminton, the result from Study 2 demonstrated that accelerometer derived load from a single upper trunk-mounted IMU were poorly correlated to lower limb RPE in adolescent Badminton players. Given the high prevalence of lower limb injuries in

Badminton, which account for between 43% and 54% of all injuries (Yung *et al.*, 2007; Guermont *et al.*, 2021), the use of lower limb-mounted IMUs may provide a more direct method for quantifying lower limb loading.

In addition to lower limb injuries, asymmetries between the lower limbs have been reported in Badminton players. Greater width and thickness of the patellar and Achilles tendon has been identified in the dominant leg (Bravo-Sanchez *et al.*, 2019), as has larger dominant leg circumference (Petrinovic *et al.*, 2015). In a study where Badminton players performed step forward lunge and jump lunge tasks, it was found that the dominant leg produced greater force across a range of metrics for both movements (Nadzalan *et al.*, 2017). Lower limb asymmetry has been shown to be associated with poorer vertical jump performance and change of direction speed in youth racket sport athletes (Madruga-Parera *et al.*, 2020) as well as being linked to injury risk across a number of sports (Helme *et al.*, 2021).

The limb symmetry index is a frequently used metric in sports medicine (Engalen-van Melick *et al.*, 2013; Abrams *et al.*, 2014) and is most commonly used as a rehabilitation target for those recovering from knee ligament injuries (Almangoush and Herrington, 2014). To that end, the value of <10% limb asymmetry is particularly common as a return to sport criterion (Schmitt *et al.*, 2012; Abrams *et al.*, 2014). This criterion has been used for strength (Brown *et al.*, 2020) and functional performance testing such as hopping distance (Almangoush and Herrington, 2014). One challenge to the use of specific tests of limb asymmetry, is whether it truly represents the ability to achieve the underlying sporting function. For example, a triple hop for distance test is not an exact representation of the functional requirements for each specific sport. Therefore, it is possible that these specific tests of limb asymmetry may mask underlying deficits in limb function during more sport specific movements. To this end, a method of measuring limb symmetry during actual play may offer new insights into limb asymmetry, especially when exploring injury risk. However, in order to achieve this, it is imperative to understand the normal limb asymmetry in a particular sport, as a high number of sports pertain to asymmetry, i.e., racket sports. Once baseline asymmetry can be established, this serves as a platform to determine whether limb asymmetry, such as <10%, is truly meaningful or just as a consequence of the asymmetrical sport.

Given the high lower limb injury prevalence in Badminton (Yung *et al.*, 2007; Guermont *et al.*, 2021), potential performance implications of lower limb asymmetry in racket sports (Madruga-Parera *et al.*, 2020) and the limitations in the specific tests of limb asymmetry, the use of lower limb-mounted IMUs may also provide a more direct measure of lower limb loading and assessment of movement asymmetry, which may have potential implications for injury management.

With the potential benefits of using lower limb-mounted IMUs for the management of injury risk and movement asymmetries, coupled with the susceptibility of the Badminton playing population to lower limb injuries and propensity for lower limb asymmetry, further study is warranted to assess the application of this method within Badminton. Study 4 will seek to (1) assess if loading calculated from upper trunk- or tibia-mounted IMUs can discriminate between players with no, uni-, bi-lateral injury history, (2) determine if Badminton players exhibit movement asymmetry during simulated match play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history.

An update to the research questions and proposed study titles and study design with the key findings from Studies 1, 2 and 3 are outlined in Table 22.

Table 22 - Proposed Research Questions, Study Title Study Design and Key Findings

Research Questions	**Study Title**	**Study Design**	**Key Findings**
Are commercially available IMUs a reliable and valid tool for quantifying Badminton specific movements?	**Study 1:** Intra- and inter-system reliability of upper body-mounted Inertial Measurement Units for the measurement of Badminton specific training load	Reliability Study	1. Different commercially available IMUs are reliable to compare Badminton specific movements. 2. Higher levels of reliability are achieved when the same IMU system is used.
Does axis specific accelerometer derived training load from an upper body-mounted IMU accurately quantify lower limb biomechanical load in Badminton players?	**Study 2:** Axis specific training load to quantify lower limb biomechanical loading in adolescent Badminton players	Correlational Study	1. Training load obtained from a single upper trunk-mounted IMU is poorly correlated to both overall RPE and lower limb specific RPE in adolescent Badminton players. 2. Axis specific training load from the vertical axis does not provide greater insight into lower limb biomechanical loading.
What are coaches perceptions towards the use of IMUs in racket sports during training and competition?	**Study 3:** Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition	Quantitative Survey	1. Racket sport coaches are supportive of the use of IMUs to assess athlete movement in training but not in competition. 2. For use in training coaches are supportive of the use of IMU placed in a number of difference positions on the trunk, arms and lower limbs.

Can limb specific load and asymmetry measurements from tibia-mounted IMUs discriminate between athletes with and without unilateral or bilateral lower limb injury history?	**Study 4:** Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history	Cross Sectional Observational Study	

Chapter 6: Study Four

6.1 Study Four: Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history

6.1.1 Research Question

Can limb specific load and asymmetry measurements from tibia-mounted IMUs discriminate between athletes with and without unilateral or bilateral lower limb injury history?

Parts of this study have been submitted for publication in:

Wylde, M.J., Callaway, A.J., Williams, J.M., Yap, J., Leow, S. and Low, C.Y. 2022. Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history. *Physical Therapy in Sport*, Under Review (see Appendix 7).

6.2 Introduction

Study 3 highlighted that racket sport coaches are supportive of the use of IMUs to assess athlete movement in training but not in competition. A number of IMU placements on the trunk, arms and lower limbs received significantly positive responses from racket sport coaches for use in training. However, the median number of IMUs that the coaches would allow to be used during training was two, demonstrating the need for careful consideration of IMU placement to maximise the potential benefits. In addition, it has been highlighted that coaches need to witness the concrete benefits and impact of technology prior to its adoption (Jaswal, 2020). It is therefore important that the benefits of the specific IMU placement are clearly understood and articulated to the coach and athlete prior to adoption.

While IMU placement on the upper trunk is common practice, Study 2 demonstrated that training load derived from single upper trunk-mounted IMU was poorly correlated to lower limb RPEs in adolescent Badminton players. This is consistent with other studies which have found that IMUs placed on the upper trunk are poor in estimating vertical acceleration of the centre of gravity and thoracic segment, and for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). This is perhaps due to the IMU being positioned far from the point of ground contact, therefore mechanical energy is absorbed and dissipated through the joints and body tissues between the foot and the IMU (Derrick *et al.*, 1998; Glassbrook *et al.*, 2020b). Given the high prevalence of lower limb injuries in Badminton, which account for between 43% and 54% of all injuries (Yung *et al.*, 2007; Guermont *et al.*, 2021), the use of lower limb-mounted IMUs may provide a more direct method for quantifying lower limb loading.

In addition to lower limb injuries, the presence of asymmetry between the lower limbs is associated with poorer jump performance, change of direction speed and agility as well as being linked to injury risk (Hoffman *et al.*, 2007; Bell *et al.*, 2014; Steild-Müller *et al.*, 2018; Madruga-Parera *et al.*, 2020; Helme *et al.*, 2021). The limb symmetry index is a frequently used metric in sports medicine (Engalen-van Melick *et al.*, 2013; Abrams *et al.*, 2014) and is most commonly used as a rehabilitation target for those recovering from knee ligament injuries (Almangoush and Herrington, 2014). To that end, the value of <10% limb asymmetry is particularly common as a return to sport criterion (Schmitt *et al.*, 2012; Abrams *et al.*, 2014). This criterion has been used for strength (Brown *et al.*, 2020) and functional performance testing such as hopping distance (Almangoush and Herrington, 2014).

In racket sports lower limb asymmetries have commonly been assessed through specific tests, such as single leg counter movement jumps, single leg broad jumps and change of direction assessments (see Table 23). A challenge with the use of these specific tests of limb asymmetry, is whether they truly represent the ability to achieve the underlying sporting function. For example, a single leg broad jump for distance test is not an exact representation of the functional requirements for each specific sport. Therefore, it is possible that these specific tests of limb asymmetry may mask underlying deficits in limb function during more sport specific movements.

Table 23 - Assessment of Lower Limb Asymmetry in Racket Sports using Specific Tests

Sport	**Measures**	**Asymmetry % (SD)**	**Reference**
Badminton	SFL		Nadzalan *et al.*, 2017
	- Absolute Peak Concentric Force	4.02	
	- Relative Peak Concentric Force	4.59	
	- Absolute Mean Concentric Force	3.79	
	- Relative Mean Concentric Force	4.17	
	- Absolute Mean Eccentric Force	4.54	
	- Relative Mean Eccentric Force	3.85	
	- Absolute Impact Force	3.71	
	- Relative Impact Force	3.60	
	-Time to Peak Force	-6.98	
	- Stance Time	-2.15	
	JFL		

	- Absolute Peak Concentric Force - Relative Peak Concentric Force - Absolute Mean Concentric Force - Relative Mean Concentric Force - Absolute Mean Eccentric Force - Relative Mean Eccentric Force - Absolute Impact Force - Relative Impact Force -Time to Peak Force - Stance Time	6.07 6.41 3.62 3.55 4.23 3.97 3.59 3.89% -7.84% -2.88%	
Badminton	SEBT – Anterior SEBT – Posteromedial SEBT – Posterolateral	2.07 -0.14 -3.00	Manolova *et al.*, 2018
Badminton	SLCMJ - Control Warm Up - Loaded Warm Up	 12.98 (7.66) 9.96 (7.75)	Yueng *et al.*, 2020
Tennis	SLCMJ SLBJ SLLJ CODS SHL - Concentric SHL – Eccentric CRO – Concentric CRO – Eccentric	15.03 (6.91) 4.14 (3.72) 6.63 (5.30) 1.83 (1.43) 7.35 (5.72) 9.82 (9.65) 9.31 (6.96) 11.18 (9.01)	Madruga-Parera *et al.*, 2020
Tennis	SLCMJ SEBT – Anterior SEBT – Posteromedial SEBT – Posterolateral SEBT – Composite CODS	14.71 (10.05) 4.76 (3.16) 4.22 (3.54) 5.49 (3.95) 3.49 (2.29) 2.09 (2.24)	Madruga-Parera *et al.*, 2019

SFL = step forward lunge; JFL = jump forward lunge; SEBT = star excursion balance test; SLCMJ = single-leg countermovement jump; SLBJ = single-leg broad jump; SLLJ – single-leg lateral jump; CODS = change of direction speed; SHL = shuffle lateral step with isoinertial device; CRO = crossover with isoinertial device.

To this end, a method of measuring limb symmetry during actual training or competition may offer new insights into limb asymmetry, especially when exploring injury risk. However, in order to achieve this, it is imperative to understand the normal limb asymmetry in a particular sport, as a high number of sports pertain to asymmetry, i.e., racket sports. Once baseline asymmetry can be established, this serves as a platform to determine whether limb asymmetry, such as <10%, is truly meaningful or just as a consequence of the asymmetrical sport.

Given the lower limb injury prevalence and potential performance implications of lower limb asymmetry in racket sports (Madruga-Parera *et al.*, 2020), a more direct measure may be required to monitor lower limb training load to assess movement asymmetry. Previously, it has been shown that lower limb-mounted IMUs were able to quantify training loads more directly that those mounted on the upper body and measure asymmetry of running in Rugby League players (Glassbrook *et al.*, 2020b). Tibia-mounted IMUs have been found to provide good-to-excellent reliability for measurement of training magnitudes during Football (Soccer) specific acceleration-deceleration, plant and cut and change of direction tasks (Burland *et al.*, 2021). Lower limb-mounted IMUs may therefore provide a more direct measure of lower limb training load and assessment of movement asymmetry, which may have potential implications for injury management.

With the potential benefits of using lower limb-mounted IMUs for the management of injury risk and movement asymmetries, coupled with the susceptibility of the Badminton playing population to lower limb injuries and propensity for lower limb asymmetry, further study is warranted to assess the application of this method within Badminton. The aims of this study were to (1) assess if training load calculated from upper trunk- or tibia-mounted IMUs can discriminate between players with no, uni-, bi-lateral injury history, (2) determine if Badminton players exhibit movement asymmetry during simulated match play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history.

6.3 Justification of Method

As discussed above, lower limb-mounted IMUs have provided a more direct method for assessing lower limb loading and asymmetries across a range of field-based sports (Glassbrook *et al.*, 2020a, Glassbrook *et al.*, 2020b, Burland *et al.*, 2021; Senington *et al.*, 2021). Within these studies, two primary placements at the lower limbs were utilised, on the tibia and on the shoe. In the study assessing accelerations of IMU on the tibia and the dorsal foot during sprinting, it was found that larger accelerations were recorded at the dorsal foot, likely due to the ankle joint motion on impact and throughout the gait cycle (Glassbrook *et al.*, 2020a). While the positioning of the IMU at the tibia is potentially more accurate than at the dorsal foot, this represents an injury risk in high impact sports such as Rugby League due to the lack of soft tissue cushioning between skin and bone (Glassbrook *et al.*, 2020a). To reduce this injury risk, in the subsequent study of Rugby League, IMU placement was on the shoe (Glassbrook *et al.*, 2020b).

As the risk of impact injuries in Badminton is less than in collision sports such as Rugby League, the need to mitigate this risk of injury is reduced and placement of the IMU on the tibia is preferred. However, the location of the IMU on the tibia has also been found to influence impact acceleration during running (Lucas-Cuevas *et al.*, 2017). In a study where IMU placement at the distal and proximal tibia was assessed during running, it was found that the distal IMU registered greater tibial acceleration peak and shock attenuation, while the distal accelerometer provided greater values for all the low-frequency measures of peak frequency, peak power, signal magnitude and shock attenuation (Lucas-Cuevas *et al.*, 2017). This study highlighted that as the location of the tibial IMU does influence the acceleration parameters, careful consideration must be made regarding the placement of the IMU so that equivalent comparisons across studies can be made.

In Badminton lower limb injuries account for between 43% and 54% of all injuries (Yung *et al.*, 2007; Guermont *et al.*, 2021), as such many Badminton players will use strapping or wear protective guards at the knee or ankle to provide the perception of extra stability during training and competition. Due to the use the strapping and guards, placement of the IMU at both the distal and proximal tibia may be problematic. Therefore, IMU placement at the mid tibia (see Figure 18) is advised for use in Badminton, as this placement provides a secure surface to attach the IMU while being away from any strapping or guards used at the ankle or knee.

Figure 18 - Placement of Tibia-Mounted IMU

As highlighted in Studies 1 and 2, a sampling frequency for accelerometer data of 100 Hz is common within the sport science literature (McLean *et al.*, 2018) and provides robust and accurate data (John *et al.*, 2019; Steels *et al.*, 2020). A sampling rate of 100 Hz will therefore continue to be used within this study. Using the acceleration data, filtering frequency was determined by residual analysis (Winter, 2009) on a sample of five athletes (see Appendix 8). Based on the residual analysis the raw data were filtered using a bidirectional 3rd order low pass Butterworth filter with cut-off frequency of 7Hz for the scapulae units, and 6Hz for the tibia units.

The sample size was for this study was determined using data from Madruga-Parera *et al.* (2019), where a mean and standard deviation of the percentage difference between limbs was calculated along with an alpha of 0.01, beta 80% and group allocation ration of 1:3. Participants in the study would be assigned into one of three groups based on injury history within the previous two years (non-injured, bilaterally injured and unilaterally injured). The two-year post-injury window was chosen as it has been demonstrated that lower limb asymmetries post anterior cruciate ligament (ACL) reconstruction can persist for up to two years (Paterno *et al.*, 2007; Sharafoddin-Shirazi *et al.*, 2020).

The data collected from the upper trunk and tibia-mounted IMUs were found to be predominantly normally distributed. This was assessed using the Shapiro-Wilk test (see Table 24). To assess the difference between the three player groups the t-test, analysis of variance (ANOVA) and Cohen's Effect Size were selected. The independent sample t-test allows for the comparison of two independent samples of numerical dependent variables (O'Donoghue, 2012). An example of this use within the study would be to compare the total training load between non-injured vs. unilaterally injured players. The ANOVA test allows for the comparison of three or more independent samples of a numerical variable (O'Donoghue, 2012). In the context of this study, this would be a comparison of the total training load between non-injured, unilaterally injured and bilaterally injured players. Cohen's Effect Size (Cohen, 1988) is often used to accompany the report of t-test and ANOVA results as Effect Sizes provide additional insight by quantifying the size of the associations and/or differences between two variables.

Table 24 - Shapiro-Wilk Test Results

	Non-Injured (P-value)	**Bilaterally Injured** (P-value)	**Unilaterally Injured** (P-value)
Total Load			
Dominant	0.99 *Normal Distribution*	0.37 *Normal Distribution*	
Non-Dominant	0.86 *Normal Distribution*	0.25 *Normal Distribution*	
Injured			0.001 *Non-Normal Distribution*
Non-Injured			0.50 *Normal Distribution*
Medio-Lateral Load			
Dominant	0.45 *Normal Distribution*	0.69 *Normal Distribution*	
Non-Dominant	0.59 *Normal Distribution*	0.22 *Normal Distribution*	
Injured			0.86 *Normal Distribution*
Non-Injured			0.69 *Normal Distribution*
Antero-Posterior Load			
Dominant	0.83 *Normal Distribution*	0.10 *Normal Distribution*	

Non-Dominant	0.37 *Normal Distribution*	0.48 *Normal Distribution*	
Injured			0.83 *Normal Distribution*
Non-Injured			0.77 *Normal Distribution*
Vertical Load			
Dominant	0.99 *Normal Distribution*	0.73 *Normal Distribution*	
Non-Dominant	0.98 *Normal Distribution*	0.53 *Normal Distribution*	
Injured			0.59 *Normal Distribution*
Non-Injured			0.28 *Normal Distribution*

Notes. Significance Level = 0.05, Outliers Included

6.4 Methods

This study utilised a cross sectional, observational study design. All data were collected during 90 minutes of simulated match play within the high-performance centre during a normal 3-hour badminton training session.

The 33 participants for this study (14 female and 19 male) were recruited from adolescent Badminton athletes based at a dedicated high-performance youth training environment (Age: 14.4 ± 1.2 y, Height: 1.65 ± 0.10 m, Mass: 54.6 ± 9.4 kg, Playing Experience: 7.3 ± 1.7 y). With institutional ethical approval, each participant and parent/guardian was provided with a participant information sheet (see Appendix 9) and was required to complete an informed consent/assent form prior to the data collection. In order to be included, athletes needed to be cleared to participate in the sport by a certified sports physiotherapist at both the stage of consent and data collection. Participants were allocated to one of three groups. Grouping was based on their injury history within the previous two years, with the *non-injured group* (19 athletes) being athletes with no injury history, the *unilaterally injured group* (8 athletes) being athletes with an injury to one lower limb and the *bilaterally injured group* (6 athletes) being athletes with an injury to both lower limbs. For the purpose of this study, injury was defined as any physical complaint or manifestation sustained by a player that results from a match or training (Pluim *et al.*, 2009), which resulted in the athlete being unable to take part in normal training by a certified sports physiotherapist for three consecutive training sessions. Post data collection, each athlete was asked to complete a questionnaire reporting any lower limb injuries sustained during the previous two years.

During the data collection, each athlete wore three VXSport (Visuallex Sport International, Lower Hutt, New Zealand) log units (dimensions: 74mm x 47mm x 17mm, weight: 50g). The upper trunk-mounted unit was worn between the scapulae in a purpose-built harness, with the remaining two units secured on the skin over the left and right mid-tibia using adhesive tape (see Figure 18). The VX Sport system has been found to possess both high intra-system and inter-system reliability compared with the Catapult Optimeye S5 system (see Study 1). Prior to the commencement of the data collection the athletes took part in a standardised team warm-up as prescribed by the coach. Training sessions lasted 90 minutes and consisted of simulated Badminton match play with multiple matches of up to 3 sets of 21 points. During the simulated match play the athletes were matched by the coach based on age, gender and playing ability. Acceleration data were recorded at 100Hz and filtered post-data collection using a bidirectional 3rd order low pass Butterworth filter with cut-off frequency of 7Hz for the scapulae units, and 6Hz for the tibia units, and mean centred in Matlab (MathWorks, Natick, MA, USA).

Load was calculated using a modified vector magnitude calculation, being the square root of the sum of the acceleration squared (Boyd *et al.*, 2011) (Equation 6) and the load for the vertical, antero-posterior and medio-lateral axis were also calculated (Equation 7). To aid comparison, the training load values for the tibia-mounted IMUs were normalised against the training load value from the upper trunk-mounted IMU.

$$Total\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2 + (ay_1 - ay_{-1})^2 + (az_1 - az_{-1})^2}{100}}$$

Equation 6: Vector Magnitude Player Load

$$Vertical\ Load = \sqrt{\frac{(az_1 - az_{-1})^2}{100}} \qquad Antero - Posterior\ Load = \sqrt{\frac{(ay_1 - ay_{-1})^2}{100}} \qquad Medio - Lateral\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2}{100}}$$

Equation 7: Vertical, Antero-Posterior, Medio-Lateral Load calculations

Asymmetry between non-dominant and dominant leg and injured and non-injured leg were calculated using the following equations (Schitlz *et al.*, 2009) (Equations 8 and 9).

$$Asymmetry = (1 - \frac{NDL}{DL}) x\ 100$$

Equation 8: Non-Dominant Leg (NDL) vs Dominant Leg (DL) Asymmetry

$$Asymmetry = (1 - \frac{IL}{NIL}) x\ 100$$

Equation 9: Injured Leg (IL) vs Non-Injured Leg (NIL) Asymmetry

Differences between the dominant and non-dominant legs, injured and non-injured legs and between the three athlete sub-groups (non-injured, bilaterally injured and unilaterally injured) were calculated using independent t-tests, ANOVA tests, both with significance set at $\leq$0.01 to accommodate for multiple testing, and Cohen's Effect Sizes (Cohen, 1988) with modified interpretative descriptors (Hopkins, 2000; Tan *et al.*, 2009): <0.20 = "trivial", 0.20 to 0.59 = "small", 0.60 to 1.19 = "moderate", 1.20 to 1.99 = "large", and >2.00 = "very large".

6.5 Results

All 33 athletes completed 90 minutes of data collection with no dropouts or data fidelity errors. Load calculated from the upper trunk-mounted IMU demonstrated non-significant differences with trivial to small effect sizes between the non-injured and bilaterally injured athlete groups (Table 25). There were moderate effect sizes observed between the non-injured and unilaterally injured groups for total load and axis specific load and between the bilaterally and unilaterally injured groups for medio-lateral load. However, these differences were outside the threshold of statistical significance ($\leq$0.01) set for this study.

Within the non-injured group, significantly higher tibia loads were observed in the non-dominant leg on the antero-posterior and vertical axis, with moderate and small effect sizes respectively (see Tables 26 and 27). The observed asymmetries ranged from -4% to 7% between the dominant and non-dominant legs (see Table 28).

Within the bilaterally injured group no significant differences were observed between the non-dominant and dominant leg across any of the axis, with trivial or small effect sizes recorded for each (see Tables 26 and 27). In all cases the observed asymmetries were within +/- 3% between the dominant and non-dominant legs (see Table 28).

Within the unilaterally injured group significantly higher tibia loads were observed on the non-injured leg for vertical load, with moderate effect sizes for total load and all axis specific loads (see Tables 26 and 27). The asymmetries recorded between the injured and non-injured leg were between 10% and 13%, with these higher loads recorded on the non-injured leg (see Table 28).

In the comparison of tibia asymmetries between the non-injured and bilaterally injured groups, no significant differences were observed but moderate effect sizes were evident for total load and vertical load (see Table 28). Between the non-injured and unilaterally injured groups significant differences were observed for antero-posterior load and vertical load (see Table 27). A large effect size was recorded for total load, with very large effect sizes recorded for antero-posterior load and vertical load. Between the bilaterally injured and unilaterally injured groups no significant differences were observed, but moderate to large effect sizes were determined for all variables (see Table 28).

Inspection of the individual athlete asymmetries demonstrates that in the non-injured athlete group the majority of athletes recorded higher loads in the non-dominant leg on the antero-posterior axis and vertical axis (see Figure 19). However, for the medio-lateral axis higher loads were predominately recorded on the dominant leg. For the bilaterally injured athletes, higher loads were predominately recorded on the dominant leg for the medio-lateral and vertical axis (see Figure 20). By contrast, the unilaterally injured athletes all recorded higher loads on the non-injured leg for total load, medio-lateral load, antero-posterior load and vertical load (see Figure 21).

Table 25 - Comparison of Axis Specific Training Load from the Upper Trunk-Mounted IMUs between Non-Injured, Bilaterally Injured and Unilaterally Injured Athlete Populations

Measure (Upper trunk-mounted IMU)	**Non Injured (N=19)**	**Bilaterally Injured (N=6)**	**Unilaterally Injured (N=8)**	**Non Injured vs. Bilaterally Injured**		**Non Injured vs. Unilaterally Injured**		**Bilaterally Injured vs. Unilaterally Injured**		**Between All Groups**
	Mean (SD)	**Mean (SD**	**Mean (SD**	**P Value**	**Effect Size**	**P Value**	**Effect Size**	**P Value**	**Effect Size**	**ANOVA P Value**
Total Load	22978.8 (4689.9)	24054.7 (5573.7)	26806.6 (4554.3)	0.64	-0.22 *Small*	0.06	-0.83 *Moderate*	0.33	-0.56 *Small*	0.19
Medio-Lateral Load	10353.9 (2053.2)	10672.2 (2058.7)	12087.8 (1986.6)	0.74	-0.16 *Trivial*	0.05	-0.86 *Moderate*	0.22	-0.71 *Moderate*	0.15
Antero-Posterior Load	10625.9 (2507.4)	11062.4 (3478.9)	12322.1 (2184.0)	0.74	-0.16 *Trivial*	0.11	-0.71 *Moderate*	0.42	-0.46 *Small*	0.32
Vertical Load	13673.4 (2893.4)	14532.2 (3141.7)	16047.5 (3037.7)	0.54	-0.29 *Small*	0.07	-0.82 *Moderate*	0.38	-0.50 *Small*	0.18

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

Table 26 - Comparison of Asymmetry within Non-Injured, Bilaterally Injured and Unilaterally Injured Athlete Populations

Measure (Tibia-mounted IMUs)	**Non-injured (N=19)**					**Bilaterally Injured (N=6)**					**Unilaterally Injured (N=8)**				
	Non Dominant - Mean (SD)	**Dominant - Mean (SD)**	**%**	**P Value**	**Effect Size**	**Non Dominant - Mean (SD)**	**Dominant - Mean (SD)**	**%**	**P Value**	**Effect Size**	**Injured - Mean (SD)**	**Non Injured - Mean (SD)**	**%**	**P Value**	**Effect Size**
Total Load	36142.7 (6709.6)	35612.9 (6971.9)	1	0.14	0.08 *Trivial*	36743.2 (7014.8)	36861.8 (5426.9)	0	0.89	-0.02 *Trivial*	36039.8 (6582.9)	40957.6 (5756.9)	-14	0.05	-0.80 *Moderate*
Medio-Lateral Load	18342.9 (3436.9)	19103.5 (3877.1)	-4	0.06	-0.21 *Small*	18977.0 (3856.6)	19351.2 (2613.5)	-2	0.65	-0.11 *Trivial*	18210.0 (3623.2)	20809.5 (2375.7)	-14	0.11	-0.86 *Moderate*
Antero-Posterior Load	16817.2 (2991.9)	15866.1 (3176.5)	6	**<0.001***	0.31 *Small*	16987.2 (3034.9)	16537.5 (2546.1)	3	0.50	0.16 *Trivial*	16448.4 (3162.2)	19051.8 (2951.1)	-16	0.05	-0.86 *Moderate*
Vertical Load	19035.9 (3830.9)	18386.7 (3738.2)	3	**0.003***	0.17 *Trivial*	19154.5 (3893.1)	19335.8 (3264.5)	-1	0.62	-0.05 *Trivial*	19437.1 (3590.4)	21559.8 (3437.1)	-11	0.02	-0.61 *Moderate*

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at 0.01 level.

Table 27 - Comparison of Normalised Asymmetry within Non-Injured, Bilaterally Injured and Unilaterally Injured Athlete Populations

Measure (Tibia-mounted IMUs)	**Non-injured (N=19)**					**Bilaterally Injured (N=6)**					**Unilaterally Injured (N=8)**				
	Non Dominant - Normalised Mean (SD)	**Dominant - Normalised Mean (SD)**	**%**	**P Value**	**Effect Size**	**Non Dominant - Normalised Mean (SD)**	**Dominant - Normalised Mean (SD)**	**%**	**P Value**	**Effect Size**	**Injured - Normalised Mean (SD)**	**Non Injured - Normalised Mean (SD)**	**%**	**P Value**	**Effect Size**
Total Load	1.58 (0.13)	1.56 (0.14)	2	0.10	0.18 *Trivial*	1.54 (0.18)	1.56 (0.21)	-1	0.56	-0.10 *Trivial*	1.36 (0.24)	1.54 (0.12)	-12	0.03	-0.94 *Moderate*
Medio-Lateral Load	1.78 (0.20)	1.86 (0.23)	-4	0.04	-0.35 *Small*	1.78 (0.22)	1.84 (0.25)	-3	0.45	-0.24 *Small*	1.54 (0.35)	1.74 (0.16)	-12	0.09	-0.74 *Moderate*
Antero-Posterior Load	1.60 (0.15)	1.51 (0.16)	7	**<0.001***	0.60 *Moderate*	1.58 (0.21)	1.57 (0.31)	3	0.71	0.07 *Trivial*	1.35 (0.26)	1.56 (0.18)	-13	0.03	-0.95 *Moderate*
Vertical Load	1.40 (0.17)	1.36 (0.17)	4	**0.002***	0.28 *Small*	1.33 (0.17)	1.35 (0.16)	-1	0.41	-0.12 *Trivial*	1.22 (0.19)	1.35 (0.14)	-10	**0.01***	-0.81 *Moderate*

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

Table 28 - Comparison of Normalised Asymmetry between Non-Injured, Bilaterally Injured and Unilaterally Injured Athlete Populations

Measure (Tibia-mounted IMUs)	**Non-injured (N=19) Non Dominant vs. Dominant**		**Bilaterally Injured (N=6) Non Dominant vs. Dominant**		**Unilaterally Injured (N=8) Injured vs. Non Injured**		**Non-injured vs. Bilaterally Injured**		**Non-injured vs. Unilaterally Injured**		**Bilaterally Injured vs. Unilaterally Injured**		**Between All Groups**
	Mean (SD)	**%**	**Mean (SD)**	**%**	**Mean (SD)**	**%**	**P Value**	**Effect Size**	**P Value**	**Effect Size**	**P Value**	**Effect Size**	**ANOVA P Value**
Total Load	1.02 (0.04)	2	0.99 (0.05)	-1	0.88 (0.12)	-12	0.28	0.63 *Moderate*	0.02	1.78 *Large*	0.06	1.06 *Moderate*	**<0.001***
Medio-Lateral Load	0.96 (0.07)	-4	0.97 (0.09)	-3	0.88 (0.18)	-12	0.81	-0.14 *Trivial*	0.23	0.75 *Moderate*	0.23	0.64 *Moderate*	0.16
Antero-Posterior Load	1.07 (0.07)	7	1.03 (0.09)	3	0.87 (0.14)	-13	0.34	0.55 *Small*	**0.01***	2.11 *Very Large*	0.02	1.31 *Large*	**<0.001***
Vertical Load	1.04 (0.04)	4	0.99 (0.04)	-1	0.90 (0.08)	-10	0.04	1.17 *Moderate*	**0.002***	2.36 *Very Large*	0.03	1.22 *Large*	**<0.001***

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

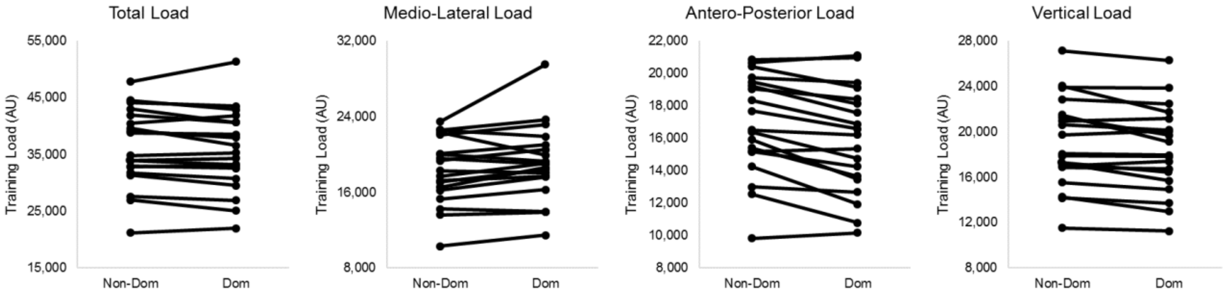


Figure 19 - Non-Injured Athlete Individual Load

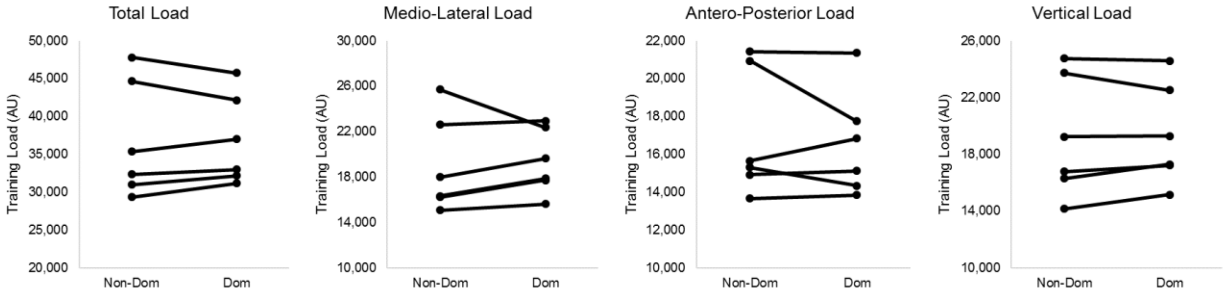


Figure 20 - Bilaterally Injured Athlete Individual Load

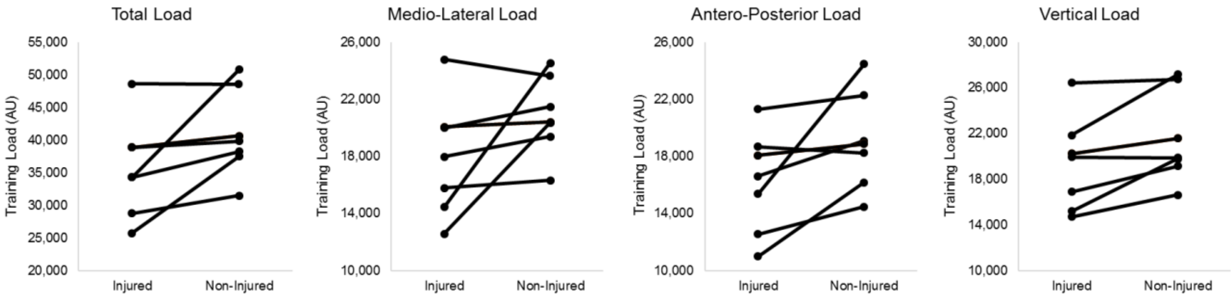


Figure 21 - Unilaterally Injured Athlete Individual Load

6.6 Discussion

The aims of this work were to (1) assess if loading calculated from upper trunk- or tibia-mounted IMUs can discriminate between players with no, uni-, bi-lateral injury history, (2) determine if Badminton players exhibit movement asymmetry during simulated match play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history.

Assessment of training load between the three groups using the upper trunk-mounted IMUs revealed no significant differences, demonstrating an inability to adequately distinguish between the groups. Upper trunk-mounted IMUs appear limited for the assessment of lower limb loading. This is consistent with the study of Rugby Union players, where upper trunk-mounted IMUs were found to be unsuitable for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). This also supports the findings from Study 2, where training loads calculated from upper trunk-mounted IMUs were found to be poorly correlated with differential ratings of perceived exertion (RPE) for the lower limbs. As upper trunk-mounted IMUs are positioned far from the point of ground contact, the mechanical energy is absorbed and dissipated through the joints and body tissues reducing the validity of the training load measures (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b). In addition, the elasticised harness used to mount the IMU to the upper trunk is a potential source of extra movement of the IMU during high intensity activities (Edwards *et al.*, 2018). Given the limitations of upper trunk-mounted IMUs for assessing lower limb loading, there is the potential for greater insights to be derived from the use of additional tibia-mounted IMUs.

Lower limb-mounted IMUs have been found to be a valid tool for detecting asymmetries during sport match play (Glassbrook *et al.*, 2020b) and therefore provide a potential means of distinguishing between athlete groups based on injury history. Using training load calculated from the tibia-mounted IMUs as a means of comparison, significant differences were observed between the dominant and non-dominant lower limbs in the non-injured group, for antero-posterior load and vertical load, with small to moderate effect sizes. The antero-posterior and vertical loads were higher on the non-dominant leg. While the movement asymmetries were comparatively small (between -4% and 7%) and below the 10% threshold for clinically significant asymmetry (Schmitt *et al.*, 2012; Abrams *et al.*, 2014; Rohman *et al.*, 2015; Kyritsis *et al.*, 2016), these findings appear contrary to evidence of structural asymmetry in the lower limbs of Badminton players (Bravo-Sanchez *et al.*, 2019; Petrinovic *et al.*, 2015) and movement asymmetry in lunge tasks (Nadzalan *et al.*, 2017), where higher values were recorded in the dominant leg. In a study of landing strategies in male Badminton players, it was found that the backhand jump smash resulted in significantly greater vertical ground reaction forces, time to peak acceleration and 50 ms impulse compared to target striking and court-based footwork (Hung *et al.*, 2020). However, there were no significant differences in the horizontal ground reaction forces between the three movements. As all the participants were right-handed and while the take off for the jump smash was from both feet, the peak accelerations were recorded on the left-side (non-dominant) foot. It is therefore likely that the decelerations recorded from jump smash landings, and similar high impact activities, where the athlete lands on the non-dominant foot, contributes to greater load being recorded in the non-dominant leg on the antero-posterior and vertical axis but not on the medio-lateral axis. While these movements create high ground reaction forces, and by extension accelerometer derived training loads, other movements such as lunges, which account for 15% of movements in Badminton (Kuntze *et al.*, 2009), may contribute to the structural asymmetries which have been observed. This may be due to the eccentric component of the movement (Fu *et al.*, 2017), which contributes to greater thickness of the muscle architecture in the dominant lower limb compared to the non-dominant limb but would not create large ground reaction forces (Bravo-Sanchez *et al.*, 2019).

While significant asymmetries in antero-posterior load and vertical load were observed towards the non-dominant leg in the non-injured group, these were not present in the bilaterally injured group, with significantly lower asymmetry observed for vertical load in the bilaterally injured group compared to the non-injured group. Given that landing from a jump smash produces high ground reaction forces (Hung *et al.*, 2020), and by extension accelerometer derived training loads, it is possible that the bilaterally injured group have developed modified movement strategies to limit the impact of these movements. In a study of Badminton players with and without knee pain, the injured group used reduced knee and upper trunk motions to complete backhand lunge tasks, with the injured players adopting a smaller centre of mass and centre of pressure displacement to reduce the load on the supporting limb (Lin *et al.*, 2015). It is likely that the athletes in the bilaterally injured group have adopted similar strategies to reduce load during high impact Badminton movements, such as the jump smash, which have resulted in lower vertical loads on the non-dominant leg.

In the unilaterally injured group, significant differences were observed on normalised vertical load, while moderate effect sizes were observed for total load, antero-posterior load and vertical load, with higher loads recorded on the non-injured leg in all cases. These asymmetries were between 10% and 13%, which are equal or above the 10% threshold commonly used for clinical decision making (Schmitt *et al.*, 2012; Abrams *et al.*, 2014; Rohman *et al.*, 2015; Kyritsis *et al.*, 2016), and were significantly higher than the non-injured group for antero-posterior load and vertical load. The mechanisms behind such alterations in limb specific training load are not immediately identifiable from the current study. As lower limb asymmetry negatively impacts vertical jump performance and change of direction speed in youth racket sport athletes (Madruga-Parera *et al.*, 2020), the clinically significant asymmetry observed in the unilaterally injured group suggests that performance of athletes in this group may be compromised.

6.7 Conclusion

The results of Study 4 demonstrate that, compared to non-injured and bilaterally injured players, those with unilateral lower limb injury had asymmetries of between 11-13%. This finding is novel due to the tibia load asymmetry being studied for the first time in Badminton players. It seems likely that Badminton players demonstrate less cumulative loading through their injured limb compared to their non-injured limb. Previous research has demonstrated ongoing limb asymmetry following unilateral limb injury. It is possible these alterations serve as a protective strategy to reduce the load on the injured limb therefore minimising the provocation of pain. Conversely, these alterations may represent sub-optimal recovery from the injury where lingering deficits in unilateral limb performance remain. This may be due to a well-documented response to pain where the body seeks to minimise the provocation of pain and protect the injured area (Bullock-Saxton *et al.*, 1994; Henriksen *et al.*, 2010; Ward, 2014). Such responses to pain and injury have been documented across other body regions (Williams *et al.*, 2010) and this adaptive response may serve as a mechanism to maintain function (in this case playing Badminton) whilst avoiding provocation and irritation of the injury. An alternate hypothesis to explain these findings suggests that this difference is a lingering impairment of function. It is well documented that following injury to a limb, widespread changes to the function of the limb are witnessed and these are known to remain, even after resolution of the pain (Ward, 2014). In this case, targeting this sub-optimal function may prove beneficial to close the symmetry gap. However, no pain was reported during or after testing questioning the hypothesis around the avoidance of pain provocation.

The values of injured limb loading are very similar to the values of limb loading demonstrated in the non-injured group. This suggests that the injured limb was being used as much as those limbs in the non-injured group. Therefore, based on the data from this study, the asymmetry seems to be driven by an increase in limb loading from the non-injured leg. This represents a truly novel finding and it is not immediate clear why such a difference was observed. It is possible that the above explanations hold true, in that there is still protection, or a lingering impairment and future investigations are needed to explore the cause-and-effect relationship through prospective work.

In current practice, a common assessment of asymmetries of injured and non-injured athlete populations involves the use of vertical jump (Impellizzeri *et al.*, 2007) or counter-movement jump protocols (Hart *et al.*, 2019). However, there is no consensus on the use of such tests in the clinical setting to monitor athletes recovering for lower limb injury (Lynch *et al.*, 2015). In addition, these methods do not account for the on court/field-based movements during training or competition (Glassbrook *et al.*, 2020b) and potentially takes athletes away from training for assessment. The use of tibia-mounted IMUs therefore provide a tool for practitioners to assess lower limb asymmetry for sport specific movements in a normal training environment. Athlete specific load asymmetries can be gathered from tibia-mounted IMUs during training with little encumbrance to the athletes' movement. Information gathered from the tibia-mounted IMUs would provide a baseline for each athlete's pre-injury loading pattern. In instances of injury, the baseline measure would provide practitioners with a benchmark to assess how close the athlete has returned to the pre-injury loading pattern during the rehabilitation process. This would complement existing jump-based asymmetry protocols and provide a sport specific assessment of the athlete's loading pattern and potentially a more accurate method of assessing the athlete's ability to return to performance.

An update to the research questions and proposed study titles and study design with the key findings from Studies 1 to 4 are outlined in Table 29.

Table 29 - Proposed Research Questions, Study Titles, Study Design and Key Findings

Research Questions	**Study Title**	**Study Design**	**Key Findings**
Are commercially available IMUs a reliable and valid tool for quantifying Badminton specific movements?	**Study 1:** Intra- and inter-system reliability of upper body-mounted Inertial Measurement Units for the measurement of Badminton specific training load	Reliability Study	1. Different commercially available IMUs are reliable to compare Badminton specific movements. 2. Higher levels of reliability are achieved when the same IMU system is used.
Does axis specific accelerometer derived training load from an upper body-mounted IMU accurately quantify lower limb biomechanical load in Badminton players?	**Study 2:** Axis specific training load to quantify lower limb biomechanical loading in adolescent Badminton players	Correlational Study	1. Training load obtained from a single upper trunk-mounted IMU is poorly correlated to both overall RPE and lower limb specific RPE in adolescent Badminton players. 2. Axis specific training load from the vertical axis does not provide greater insight into lower limb biomechanical loading.

What are coaches perceptions towards the use of IMUs in racket sports during training and competition?	**Study 3:** Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition	Quantitative Survey	1. Racket sport coaches are supportive of the use of IMUs to assess athlete movement in training but not in competition. 2. For use in training coaches are supportive of the use of IMU placed in a number of difference positions on the trunk, arms and lower limbs.
Can limb specific load and asymmetry measurements from tibia-mounted IMUs discriminate between athletes with and without unilateral or bilateral lower limb injury history?	**Study 4:** Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history	Cross Sectional Observational Study	1. Training load from tibia-mounted IMUs can differentiate between adolescent Badminton players with and without unilateral and bilateral lower limb injury history. 2. Tibia-mounted IMUs provide a tool to assess lower limb asymmetry for Badminton specific movements in a normal training environment.

Chapter 7: Discussion

7.1 Discussion

The aims of this project were to provide insight into the use of IMUs for the assessment of training load and identification and detection of asymmetries associated with injury within a population of Badminton players. The use of wearable technologies, including IMUs, has become increasingly prevalent in both field-based and court-based sports. However, despite being amongst the most watched and played sports in the world (Kwan *et al.*, 2010), the application of IMUs within Badminton remains comparatively under researched when compared to field-based sports, such as Football and Rugby codes, and other court-based sports, such as Basketball, Netball and Tennis (Phomsoupha and Laffaye, 2014). Given the high injury rates within Badminton, as high as 11.6 per 1000 playing hours in matches (Guermont *et al.*, 2021), and the high proportion of lower limb injuries, between 43% and 54% of all injuries in an elite Badminton playing population (Yung *et al.*, 2007; Guermont *et al.*, 2021), the sport provided an ideal environment to assess the use of IMUs for quantifying lower limb loading and assessing limb loading asymmetries to facilitate decision making for the rehabilitation and return to play process.

7.1.1 Reliability and Validity

IMUs are light, portable, inexpensive, easy to set up, allow for rapid evaluation of a large number of athletes (Picerno *et al.*, 2011) and enable athletes to be monitored in an indoor training environment (Boyd *et al.*, 2011). However, while there have been examples of intra-system (within system) reliability assessments of the use of IMUs (Boyd *et al.*, 2011; Van Iterson *et al.*, 2017; Luteberget *et al.*, 2018) there was a lack of studies assessing inter-system (between systems) reliability. While similar studies had been conducted for the use of semi-automated tracking systems and GPS (Buchheit *et al.*, 2014), there were no studies regarding the inter-system reliability of IMUs within commercially available athlete monitoring systems. Understanding the inter-system reliability is essential for practitioners to know if data obtained from one system is comparable to data obtained from a different system.

Study 1 therefore sought to assess the intra- and inter-system reliability of the accelerometer derived data from IMUs. The intra-system reliability assessment of the VX Sport Log units demonstrated a high level of reliability. For the inter-system reliability assessment, where the VX Sport Log units were compared against the Catapult Optimeye S5 units, generally good levels of reliability were also found. However, it was found that the difference between the two systems increased the longer the duration of the assessment continued. Upon further inspection, it was found that one, or both, of the systems were not capturing at a true 100Hz, with a 0.25% difference between the two system. Once both datasets were resampled this difference was no longer apparent.

These findings further emphasise the importance of practitioners understanding the sampling rates, frequency cut-offs and data processing algorithms used within the “black box” of commercially available athlete monitoring systems

(Malone *et al.*, 2017). As these sampling rates, frequency cut-offs and data processing algorithms are often proprietary to the manufacturer of the athlete monitoring system, it is potentially difficult to compare between systems. Therefore, when comparing data from different systems, practitioners are advised to extract the raw data for processing, to ensure consistency and facilitate comparison of the data between systems.

In Study 4, residual analysis was conducted to ensure that appropriate frequency cut-offs were applied to the accelerometer data obtained from the upper trunk and tibia-mounted IMUs (Winter, 2009). To demonstrate the impact of the cut-off frequencies and data processing, Table 30 includes data collected from the same athlete under four different conditions, with or without filtering (bidirectional 3rd order low pass Butterworth filter with cut-off frequency of 7Hz for the upper trunk units, and 6Hz for the tibia units) and mean centering. Comparison between the "Non-Filtered and Non-Mean Centered" values and the "Filtered and Mean Centered" values, shows differences of 90 to 97.3%, highlighting the impact of filtering and data processing. Given the difference that filtering and data processing can have on the interpretation of data collected from athletes, it is essential that practitioners equip themselves with the knowledge and skillsets to understand and manage these effects when working in an applied setting.

Table 30 - Example Load Data Under Four Filtering and Mean Centering Conditions

Condition	**Total Load (AU)**	**Medio-Lateral Load (AU)**	**Antero-Posterior Load (AU)**	**Vertical Load (AU)**
Upper Trunk				
Non-Filtered and Non-Mean Centered	527,100	86,754	236,760	431,980
Non-Filtered and Mean Centered	522,680 *(-0.8%)*	84,021 *(-3.2%)*	235,050 *(-0.7%)*	430,340 *(-0.4%)*
Filtered and Non-Mean Centered	39,785 *(-92.5%)*	16,377 *(-81.1%)*	17,278 *(-92.7%)*	23,920 *(-94.5%)*
Filtered and Mean Centered	19,058 *(-96.4%)*	8,575 *(-90.1%)*	7,972 *(-96.6%)*	11,848 *(-97.3%)*
Right Tibia				
Non-Filtered and Non-Mean Centered	629,070	192,030	229,240	477,870
Non-Filtered and Mean Centered	586,500 *(-6.8%)*	141,600 *(-26.3%)*	216,690 *(-5.5%)*	468,430 *(-2.0%)*
Filtered and Non-Mean Centered	140,220 *(-77.7%)*	86,338 *(-55.0%)*	51,788 *(-77.4%)*	66,842 *(-86.0%)*
Filtered and Mean Centered	35,354 *(-94.4%)*	17,972 *(-90.6%)*	15,657 *(-93.2%)*	19,240 *(-96.0%)*
Left Tibia				
Non-Filtered and Non-Mean Centered	634,560	195,350	211,960	489,640
Non-Filtered and Mean Centered	585,300 (-7.8%)	144,680 (-25.9%)	190,310 (-10.2%)	479,450 (-2.1%)
Filtered and Non-Mean Centered	157,500 (-75.2%)	96,805 (-50.4%)	60,667 (-71.4%)	74,232 (-84.8%)
Filtered and Mean Centered	36,989 (-94.2%)	19,622 (-90.0%)	16,832 (-92.1%)	19,269 (-96.1%)

In an elite sport setting decisions on training prescription, team selection and game tactics can be impacted by data obtained from IMUs and other wearable technologies. Given the potential impact of data obtain from these systems, it is essential that the reliability and the validity is established (O'Donoghue and Longville, 2004). Study 1 established the reliability and validity of an upper trunk-mounted IMU for the assessment of Badminton specific movements and provides practitioners with assurance regarding the use of IMUs for this purpose and that the feedback provided to athletes and coaches is a true representation of what has actually taken place during training and/or competition. In addition, as a high degree of inter-system reliability was established, practitioners can be confident of using data collected from different athlete monitoring systems to compare athletes when required.

7.1.2 Coach/Athlete Acceptance

Even once the reliability of a system or approach has been established, practitioners are often required to consider the, sometimes-competing, demands of reliability, construct validity and athlete/coach acceptance. For example, while multi-camera motion capture systems, such as Vicon, are normally considered as the "gold standard" for the assessment of athlete movement (Duffield *et al.*, 2009), these systems often take the athlete out of their normal performance environment, potentially impacting the construct validity of the assessment of movement (Zak, 2014). In the comparatively common task of walking, the number of scientists involved in the testing protocol within a lab setting has been found to effect gait speed, cadence, stride length and step duration (Friesen *et al.*, 2020). This effect when applied to the more complex movements of elite athletes, would mean that the movement assessed in a lab environment may not be an accurate reflection of the athletes' movement in a training or competition setting. A key advantage of the use of IMUs is that their use allows athletes to perform normal movements with little encumbrances in their normal training environment rather than in a lab setting (Zak, 2014). The use of IMUs can therefore provide a more realistic, or valid, assessment of actual athlete movement.

While the reliability and construct validity of the use of IMUs to assess Badminton specific movements have been established, the third aspect under consideration by practitioners, athlete/coach acceptance, has yet to be accounted for. Within the current body of research, there are few studies which have sought to assess coach or athlete perceptions towards the use of wearable technologies, such as IMUs. In one of the few studies of coaches' perception towards the use of wearable technologies, 73% of NCAA and professional sport coaches reported frustrations with wearable technologies due to inaccurate data, lack of meaningful recommendations and challenges in getting the technology to work consistently (Luczak *et al.*, 2020). Perhaps more of a concern for practitioners is that respondents also highlighted that athletes were reluctant to use wearable technologies due to the perceived lack of comfort, inconvenience, appearance and concerns that they are being tracked (Luczak *et al.*, 2020). In a separate study of elite coaches, 36% highlighted athlete acceptance as a challenge in implementing wearable technology, while 27% highlighted a lack of support or acceptance from other coaches (Jaswal, 2020).

Given the gap in the research pertaining to coaches' perception towards the use of wearable technologies, especially for racket sport coaches, Study 3 sought to understand the perception of racket sport coaches towards the use of IMUs during training and competition. Within this study, a significant majority of racket sport coaches indicated that they would allow their athletes to use IMUs during training and a non-significant majority indicated they would allow their athletes to use IMUs during competition. However, when enquired regarding the placement of the IMUs for use during competition, no placement received a significantly positive response, with significantly negative responses received for 11 proposed placements. It is likely that the concerns regarding athlete reluctance to use the IMUs (Luczak *et al.*, 2020; Jaswal, 2020) had impacted the racket sport coaches' perception towards use during competition. While the need to witness the concrete benefits and impact of technology was highlighted as a major factor in the coaches' decision to adopt a technology (Jaswal, 2020), this is an area that is potentially overlooked by practitioners when seeking to introduce a new technology to coaches. Relative advantage, compatibility, complexity, trial-ability and observability are key factors in the persuasion stage of innovation adoption (Rogers, 2003). Practitioners are therefore recommended to spend time to address these areas with coaches to enhance acceptance and impact the adoption of wearable technologies.

While no IMU placement was found to have a significantly positive response from racket sport coaches for use during competition, nine IMU placements received significantly positive responses for use during training. IMU placement on the Upper Trunk, Lower Trunk, Dominant Wrist, Non-Dominant Wrist, Non-Dominant Lower Arm, Dominant Upper Arm, Non-Dominant Upper Arm, Lower Leg and Shoe were all found to have significantly positive responses from racket sport coaches for use during training. However, the response from the racket sport coaches highlighted a median value of two IMUs to be worn by the athletes during training.

As a close relationship and common understanding between the sport scientist and the coach is required when planning data collection and developing performance analysis outputs (Bampouras *et al.*, 2012), it is essential that practitioners carefully consider the preferences of coaches when designing interventions. As highlighted in Study 3, while coaches were supportive of the use of IMUs during training, the median number of units was only two per athlete. Considering these findings, it is vital that practitioners select the placement of the IMUs carefully to ensure that the data collected is meaningful and provides insights to inform the decision making of coaches. The consideration of coaches' preferences coupled with the delivery of meaningful and impactful insights has the potential to create a positive feedback loop, which will further strengthen the collaborative effort between coaches and practitioners and result in greater coach acceptance of the use of IMUs.

7.1.3 Upper Trunk IMU Placement

In the majority of field- and court-based sports the athlete tracking units are predominately worn on the upper trunk, between the scapulae in a purpose-built harness. The placement of the unit on the upper trunk is for athlete comfort and safety, especially in high impact sports such as both Rugby codes and Australian Rules Football. In the context of these sports, the IMUs are primarily used to assess collisions, as the locomotive aspects of athlete movement are assessed via GPS. However, it was found that isolating the load from the antero-posterior and medio-lateral axis provided a more accurate quantification of these collisions compared to the combined load from all axes. This was due to load from the vertical axis from running based activities masking the changes in load from the collisions (McLean *et al.*, 2018). In a Badminton context, exploring the inverse was of interest, as accelerations in the antero-posterior and medio-lateral axis may mask the changes in load from the vertical axis. Few studies of court-based sports reported axis specific load (Fish and Grieg, 2014), however this is an area that warranted further investigation.

As such, Study 2 sought to establish if load from the vertical axis provided an improved measure for lower limb loading, compared to total load and axis specific load for the antero-posterior and medio-lateral axis. The findings from this study demonstrated that the vertical load was more strongly correlated to the RPE score for breathlessness (RPE-B) compared to the RPE score for lower limb fatigue (RPE-L), however, both correlations were very weak. All of the correlations between the load values (total and axis specific) and RPEs for breathlessness and lower limb fatigue were weak or very weak. There are a number of possible explanations, including the issue of accelerometer derived load not accounting for “low load, high RPE” movements, such as holding an isometric squat while waiting for an opponent’s shot. However, the main limitation with this approach appeared to be the placement of the unit on the upper trunk. Firstly, during certain movements, for example a lunge, there is a misalignment between the orientation of the unit and the orientation of the athlete. Secondly, the placement of the unit on the upper trunk is far from the point of ground contact resulting in mechanical energy being absorbed and dissipated through the joints and trunk tissues between the foot and the IMU (Derrick *et al.*, 1998; Lucas-Cuevas *et al.*, 2017; Glassbrook *et al.*, 2020b). This finding was supported by a study of Rugby Union players, which found that upper trunk-mounted IMUs exhibited poor reliability and were non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018).

Following Study 2, in an attempt to maintain the conventional sensor placement at the upper trunk while overcoming the issues presented due to this placement, a machine learning approach was explored. The application of machine learning in a sports context has been increasing able to identify specific movements using data derived from IMUs (Crust *et al.*, 2018). A machine learning approach has been used in Badminton, using two wrist-worn IMUs to identify stroke type (serve, clear, drop or smash) (Anand *et al.*, 2017). In Cricket fast bowling, accelerometer and gyroscope data from an upper trunk mounted IMU were able to differentiate between bowling and non-bowling actions (McNamara *et al.*, 2015). A number of conditions were required to differentiate between bowling and non-bowling actions, including run-up velocity from the GPS sensor, back-foot contact from the accelerometers and “roll like” rotation from the gyroscopes. A similar approach may have provided further insights into the loading mechanism in Badminton by combining accelerometer data from take-offs and landings and gyroscope data from upper body rotations to identify Badminton specific movements, for example jump smashes and lunges.

The machine learning approach was piloted with data obtained from a single male University-level Badminton player. The pilot trial was manually digitalised using Kinovea (Roubaix, France) to identify temporal points of jumps and lunges. Data from the accelerometer and gyroscope at these time points were then used to train four machine learning models to identify these movements (using the 75% training and 25% testing approach). Within the training dataset of 7,835 entries, there were 43 lunges and 22 jumps, which were used to teach the four machine learning models (K-Nearest Neighbour, Logistic Regression, Naïve Bay and Support Vector Machine). Within the testing dataset of 2,612 entries there were 14 lunges and 7 jumps. However, these machine learning approaches were unable to identify the movements within the datasets, see Table 31.

Table 31 - Machine Learning Results from Pilot Study with One Badminton Player

		K-Nearest Neighbour		Logistic Regression	
		Predicted (N)	Predicted (Y)	Predicted (N)	Predicted (Y)
Jumps	Actual (N)	2605	0	2605	0
	Actual (Y)	7	0	7	0
Lunges	Actual (N)	2598	0	2598	0
	Actual (Y)	14	0	14	0
		Support Vector Machine		**Naïve Bay**	
Jumps	Actual (N)	2605	0	2436	162
	Actual (Y)	7	0	10	4
Lunges	Actual (N)	2598	0	2604	1
	Actual (Y)	14	0	7	0

The K-Nearest Neighbour, Logistic Regression and Support Vector Machine models provided the same outcomes and each failed to correctly identify the jumping and lunging movements. While the Naïve Bay model fared slightly better by correctly identifying four of the jumps, there were a total of 172 incorrect predictions. The Naïve Bay model also failed to correctly identify any of the lunging movements.

The results from this pilot study highlighted the limitations in the machine learning approach. Even for comparatively common movements such as jumps and lunges, the frequency of these movements were insufficient to successfully train a machine learning model. While adding in data from more training sessions may have strengthened the predictive abilities of the models for the individual athlete under investigation, it is unlikely that this model could be applied to other athletes due to individual differences in movement. A potential limiting factor for the models is the high degree of noise within the dataset.

The placement of the IMU on the upper trunk provided a poor measure of lower limb loading due to the distance from the point of ground contact. The dispersion of mechanical energy through the joints and trunk tissues between the foot and the IMU create addition noise which limits the ability of the machine learning models to successfully predict the jumping and lunging movements. The use of additional IMUs may strengthen the predictive ability of the models by providing additional data points to potentially improve the accuracy of the models. As the upper-trunk mounted IMUs provide a poor measure of lower limb loading in Badminton players, the use of IMU for this purpose should be avoided and a more appropriate placement of the IMUs for the assessment of lower limb loading is required.

7.1.4 Lower Limb Placement

The results from Study 2 demonstrated the limitation of the upper trunk IMU placement for assessing lower limb loading in Badminton players. These results are similar to those of field-based sports, were upper trunk-mounted IMUs were found to exhibit poor reliability and were non-valid in estimating vertical acceleration of the centre of gravity and thoracic segment nor for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). Given these limitations, the placement of IMUs on other parts of the body warranted further investigation.

The results of Study 3 highlighted that while racket sport coaches are reluctant for their athletes to use IMUs during competition, they are accepting of the use of IMUs during training. In particular, the placement of IMUs on the Upper Trunk, Lower Trunk, Dominant Wrist, Non-Dominant Wrist, Non-Dominant Lower Arm, Dominant Upper Arm, Non-Dominant Upper Arm, Lower Leg and Shoe received significantly positive responses from the racket sport coaches. Of these potential IMU placements, the placement on the Lower Leg is of particular interest as it provides a more direct measure of lower limb loading. In the study of field-based sports, limb-mounted IMUs have been used to measure accelerations (Glassbrook *et al.*, 2020a), impact loading and step counts (Burland *et al.*, 2021) and to assess lower limb asymmetry (Glassbrook *et al.*, 2020b).

In addition to the ability to measure lower limb loading more directly, lower limb-mounted IMUs provide the advantage of being able to measure lower limb asymmetries during court-based movements. Lower limb asymmetries have been linked with poorer vertical jump performance and change of direction speed in youth racket sport athletes (Madruga-Parera *et al.*, 2020) as well as being linked to injury risk across a number of sports (Helme *et al.*, 2021). In studies of Badminton players, greater width and thickness of the patellar and Achilles tendon have been found in the dominant leg (Bravo-Sanchez *et al.*, 2019), as have larger dominant leg circumference (Petrinovic *et al.*, 2015). In addition, it was found that greater force was produced in the dominant leg during step forward lunge and jump lunge tasks (Nadzalan *et al.*, 2017). The ability to assess movement asymmetries during court-based training could therefore provide practitioners with a valuable tool in managing athletes load, tracking lower limb asymmetry and decreasing injuries.

Based on the above, Study 4 sought to (1) assess if load calculated from upper trunk- or tibia-mounted IMUs was able to discriminate between players with no, uni-, bi-lateral injury history, (2) determine if Badminton players exhibit movement asymmetry during simulated match play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history. Consistent with the findings from Study 2, the upper trunk-mounted IMU was unable to distinguish between the non-injured, unilaterally injured and bilaterally injured groups, with no significant differences observed. While some correlations were observed between the upper trunk-mounted and tibia-mounted IMUs (see Table 32), the R-values of around 0.8 equate to an R-squared of 0.64, suggesting that there is 36% unexplained variance between the IMUs based on position. This variance is potentially greater than that which would be observed between training sessions, further limiting to use of upper trunk-mounted IMUs for regular training load monitoring.

Table 32 - Comparison Between the Upper Trunk- and Tibia-Mounted IMUs (n=33)

Measure	**Upper Trunk – Mean (SD)**	**Tibia (Dom) – Mean (SD)**	**Tibia (Non-Dom) – Mean (SD)**	**R Value - Upper Trunk to Dom**	**R Value - Upper Body to Non-Dom**	**R Value - Dom to Non-Dom**
Total Load	24150.4 (4857.5)	37131.5 (7259.5)	37376.2 (6878.9)	0.87 *Very Strong*	0.88 *Very Strong*	0.97 *Very Strong*
Medio-Lateral Load	10848.5 (2076.3)	19738.5 (3792.9)	19043.3 (3469.9)	0.74 *Strong*	0.80 *Very Strong*	0.90 *Very Strong*
Antero-Posterior Load	11155.8 (2602.4)	16641.2 (3370.9)	17361.9 (3149.7)	0.81 *Very Strong*	0.87 *Very Strong*	0.94 *Very Strong*
Vertical Load	14427.6 (2994.3)	19248.4 (4012.4)	19643.3 (3905.9)	0.83 *Very Strong*	0.82 *Very Strong*	0.97 *Very Strong*

Notes. SD; standard deviation, Dom; dominant limb, Non-Dom; non-dominant limb.

While upper trunk-mounted IMUs are limited for the measurement of lower limb loading, the use of tibia-mounted IMUs enabled the detection of asymmetries between lower limbs. For the non-injured group, the observed asymmetries were statistically significant for antero-posterior and vertical load, but below the 10% threshold commonly used for clinical asymmetry (Schmitt *et al.*, 2012; Abrams *et al.*, 2014; Rohman *et al.*, 2015; Kyritsis *et al.*, 2016), suggesting that these asymmetries were not detrimental to performance. The higher loads on the antero-posterior and vertical axes, were observed on the non-dominant leg. While this initially appeared contrary to the structural asymmetries observed in Badminton players, where higher values were recorded on the dominant leg (Petrinovic *et al.*, 2015; Bravo-Sanchez *et al.*, 2019), it is likely that the higher accelerometer derived loads observed on the non-dominant leg were a result of landings after jump movements, such as the overhead smash (Hung *et al.*, 2020). In contrast, no significant differences were observed in the bilaterally injured group, suggesting that this group had adopted a modified movement pattern to reduce loading to protect the lower limbs or in response to previous or current pain (Lin *et al.*, 2015).

In the unilaterally injured group significant differences were observed for normalised vertical load, while moderate effect sizes were observed for total load, antero-posterior load and vertical load. In all cases higher loads were observed on the non-injured leg, with the asymmetries ranging from 11 to 13% (10 to 13% when normalised), which is above the threshold of structural asymmetry (Schmitt *et al.*, 2012; Abrams *et al.*, 2014; Rohman *et al.*, 2015; Kyritsis *et al.*, 2016). These results suggested that the unilaterally injured athletes are increasing the load on their non-injured leg, possibly to protect the previously injured limb as a protective strategy and/or to reduce pain. The values of injured limb loading are very similar to the values of limb loading demonstrated in the non-injured group. This suggests that actually the injured limb was being used as much as those limbs in the non-injured group, suggesting that the asymmetry was driven by an increase in limb loading from the non-injured leg.

The combined results from Studies 2 and 4 highlight the limitations in the use of upper trunk-mounted IMUs. Training load calculated from upper trunk-mounted IMUs was weakly correlated with differential RPE for the lower limbs in Study 2 and demonstrated a high degree of unexplained variation when compared to load calculated from the tibia-mounted IMUs in Study 4. By contrast, the tibia-mounted IMUs provided a more direct measure of lower limb loading and were able to highlight clinically significant lower limb load asymmetries in unilaterally injured athletes. The latter finding is of particular importance as the ability to assess lower limb asymmetries during training has implications for return to training protocols. It is common for lower limb asymmetries of injured and non-injured athlete populations to be assessed using vertical jump (Impellizzeri *et al.*, 2007) and/or counter-movement jump protocols (Hart *et al.*, 2019). However, there is no consensus on the use of such tests in the clinical setting to monitor athletes recovering for lower limb injury (Lynch *et al.*, 2015). The use of tibia-mounted IMUs therefore provides a tool for practitioners to assess lower limb asymmetry for sport specific movements in a normal training environment.

As found in Study 3, racket sport coaches are accepting of the use of lower limb mounted IMUs during training, if not in competition, suggesting that practitioners would experience few issues in implementing this technology. Information obtained from non-injured athletes during training could be used to create a baseline measure for each athlete. In the event of an injury, these baseline measures could be used to assess how closely the injured athlete has returned to their pre-injury movement pattern. The use of tibia-mounted IMUs could complement existing jump-based asymmetry protocols and provide a sport specific assessment of the athlete’s loading pattern, harnessing the strength of IMUs in allowing athletes to perform normal movements in their normal training environment (Zak, 2014). Allowing athletes to return to training more safely and potentially minimising the risk of re-injury, would enable coaches to witness the concrete benefits and impact of the technology (Jaswal, 2020), potentially allowing IMUs to be used more widely in both training and competition.

7.2 Key Findings

The key findings from this thesis, which were not well understood prior to the commencement of the research, can be summarised as follows:

- It is reliable to use data from different IMU systems (namely VX Sport Log and Catapult Optimeye S5) to compare Badminton specific movements. However, higher levels of reliability are achieved if the same system is used.
- Training load obtained from a single upper trunk-mounted IMU is poorly correlated to both overall RPE and lower limb specific RPE in adolescent Badminton players.
- Axis specific training load from the vertical axis does not provide greater insight into lower limb biomechanical loading compared to overall training load in adolescent Badminton players.
- Racket sport coaches are supportive of the use of IMUs to assess athlete movement in training but not in competition.
- For use in training, coaches are supportive of the use of IMUs placed in a number of difference positions on the trunk, arms and lower limbs.

- Training load from tibia-mounted IMUs is able to differentiate between adolescent Badminton players with and without unilateral and bilateral lower limb injury history.
- The use of tibia-mounted IMUs provide a tool for practitioners to assess lower limb asymmetry for Badminton specific movements in a normal training environment.

7.3 Limitations

A common limitation with studies of elite athlete populations are the comparatively small sample sizes. In studies of elite athlete populations, there is a common tension between the inherently small number of elite athletes (and therefore lack of study participants) and the high relevance of even tiny differences, which regularly leads to a mismatch of required and achievable sample size (Skorski and Hecksteden, 2021). This tension can be exacerbated further in the study of high-level youth athletes, as access to this population can be limited due to competing demands placed on these athletes (academic, training, recovery etc.). For each of the studies in the current thesis sample size calculations were used to ensure that suitable sample sizes were obtained. However, for other research questions it may not be possible to obtain access to a sufficient sample of elite youth athletes at a single training centre. This restriction may be overcome through greater collaboration between elite youth athlete training centres to increase the size of the population under investigation.

A further limitation was that the IMUs used, VX Sport Log units, were designed to be used between the scapulae in a purpose-built harness and not used on the lower limbs. In Study 4 the IMUs were attached to the mid-tibia using adhesive tape. While this was feasible for the purpose of the study, the use of this type of unit would make longitudinal studies and daily monitoring difficult. Other brands of IMU, for example IMeasureU Blue Trident (Vicon Motion Systems Ltd, Oxford, UK) and Xsens DOT (Xsens Technologies B.V., Enschede, Netherlands), which are specifically designed to be worn at the lower limbs and are smaller (VX Sport Log: 74mm; IMeasureU Blue Trident: 42mm; Xsens DOT: 36mm) and lighter (VX Sport Log: 50g; IMeasureU Blue Trident: 9.5g; Xsens DOT: 11.2g) than the VX Sport units (see Figure 22). These units also come with a purpose-built strap which allows the units to be worn at the distal tibia (see Figure 23). The use of these smaller units would facilitate smoother data collection and allow for longitudinal studies of lower limb loading in Badminton and other court-based sports to be conducted

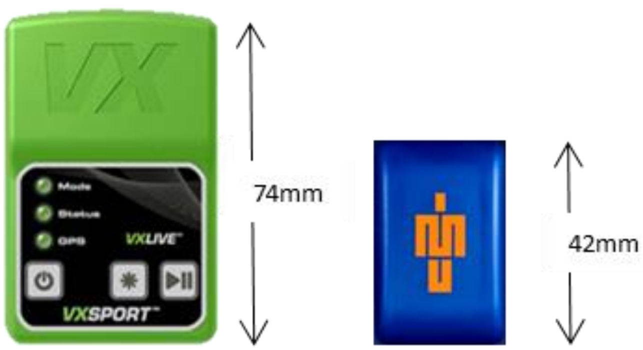


Figure 22 - Comparison of VX Sport Log Unit and IMeasureU Blue Trident Unit

Figure 23 - Example of Xsens Dot unit with Strap Placed at the Distal Tibia

7.4 Future Research

Based on the findings on this thesis there are a number of areas which may warrant further research.

As discussed in Study 3, the preferences of coaches (and athletes) are rarely considered during the adoption of new technologies and sport science approaches. However, these preferences often play an essential role in the adoption of these technologies and approaches in an applied setting. Therefore, further study is warranted using larger samples sizes of sport, level and/or age specific coaches to further understand the preferences within each of these distinct populations. In addition, the preferences of athletes would also provide further insight into the factors that potentially impact the adoption of new technologies and approaches. Findings from such studies would provide practitioners with important insights regarding the design, communication and implementation of new technologies and sport science approaches within the specific environments in which they operate.

The findings from Study 4 highlighted the benefits of the use of tibia-mounted IMUs to assess lower limb loading and asymmetries in adolescent Badminton players. As this was a cross sectional study, the observations represented a single time point of the adolescent Badminton players in terms of physical development and/or recovery from injury. Further insights would be garnered through the use of tibia-mounted IMUs as a regular monitoring tool within a single population over a longitudinal period. The development of smaller IMUs which are easier to mount on the tibia mean that such longitudinal studies are now more feasible and the longitudinal study design allows for changes in lower limb asymmetry and training load profiles to be tracked over time to understand changes based on physical development and during the build up to and recovery from lower limb injuries. As highlighted in the limitations section, such studies could be further strengthened through strategic collaborations between elite youth training centres to pool resources and increase the size of the populations under investigation. Such collaborations would enable more meaningful findings to be uncovered, which would impact the design of training programmes for youth Badminton players to enhance development and reduce injury risk through age-appropriate training load prescription.

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Appendix 1

Wylde, M.J., Lee, M.B.C., Low, C.Y. and Callaway, A.J. 2018. Reliability and validity of GPS-embedded accelerometers for the measurement of badminton specific player load. *Journal of Trainology,* 7(2), 34-37.

Link to Journal Article:

http://eprints.bournemouth.ac.uk/31582/8/v7-2%2008%20p34-37%20Wylde%20et%20al.pdf

Appendix 2

Participant Information Sheet

Project Title: Validation of VX Sport IMUs as a tool for measuring Badminton specific movements

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Invitation

You are being invited to take part in a research project. Before you decide to participate it is important for you to understand why the research is being conducted and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask one of the research team if there is anything that is not clear or if you would like more information.

Background

Inertial measurement units (IMUs) have been used to assess athlete movement across a number of different sports. However, to date there has been no evaluation of VX Sport (VX Sport, Lower Hutt, New Zealand) IMUs with court-based sports, such as Badminton. To validate these units for measuring Badminton specific movements both intra- and inter-system reliability assessments are required.

Aims

- To investigate the intra-system reliability between two VX Sport IMUs for measuring Badminton specific movements.
- To investigate the inter-system reliability between one VX Sport IMU and one Catapult IMU (Catapult Innovations, Melbourne, Australia) for measuring Badminton specific movements.

Duration

The test will be conducted at the Singapore Sports School and will last a maximum duration of 1 hour.

Why were you chosen?

You have been selected as you are a recreational Badminton player with at last 5 years Badminton playing experience.

Do I have to take part?

You can decide to not take part at any time. You can refuse further participation during the tests for any reason. This research investigation is entirely voluntary. If you do decide to take part, you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time without repercussions or affecting any benefits that you are entitled to in any way. You do not have to give a reason.

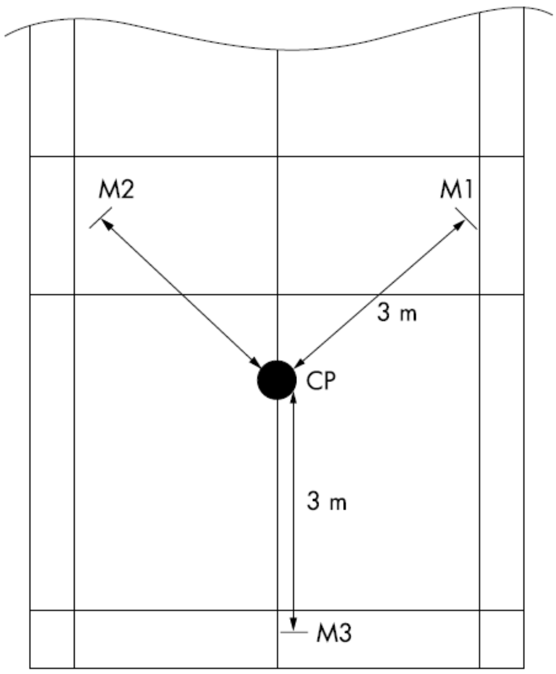
What do I have to do?

You will be asked to wear either two VX Sport IMUs, or one VX Sport IMU and one Catapult IMU (see Figure 1) located between the scapulas in purpose built harnesses. The approximate weight of each IMU is 50 grams.

Figure 1 – VX Sport and Catapult Inertial Measurement Units

You will be asked to perform a warm up of your choice prior to the commencement of the test. Following the warm up you will be asked to perform the Badminton specific incremental test in an area the size of one half of a Badminton singles court (see Figure 2).

Figure 2 – Diagram of Badminton specific incremental fitness test (Wonisch *et al.*, 2003[1])



From a central point you will start following a signal given by a whistle, move 3 m forward to a marker at the right side of the court, touch the net with your racket and move immediately back to the central point. On the next signal you will move to a second marker at the left side of the court, touch the net with your racket and move back again. On the next signal you will move backwards to a third marker 3 m behind the central point, perform a jump turn at the centre line and carryout a simulated smash. Once you return to the central point the procedure repeats and continues until voluntary exhaustion. Signals are given from a pacer with the velocity at the beginning of the test being 0.60 m/s, with six signals per minute. The velocity is increased every minute by 0.10 m/s, with one additional signal per minute.

[1] Wonisch, M., Hofmann, P., Schwaberger, G., von Duvillard, S.P. and Klein, W. (2003). Validation of a field test for the non-invasive determination of badminton specific aerobic performance. British Journal of Sports Medicine, 37, 115-118.

What are the possible disadvantages and risks of taking part?

Overall the risks associated with the Badminton specific incremental fitness test are minimal but to help manage any risk you will be asked to complete a physical activity readiness questionnaire (Par-Q) prior to starting the test. If you answer “Yes” to one or more of the Par-Q questions you will not be able to undertake the test.

What are the possible benefits of taking part?

The information provided from the Badminton specific incremental fitness test will give you a Badminton specific fitness benchmark.

Will my taking part in this project be kept confidential?/ What will happen to the results of the research project?

Your identity and any information will always remain confidential and only be known to the researching team. The raw data analysis itself will be stored by the principal investigator at the Singapore Sports School.

NOTE: The results of this experiment will potentially form part of future scientific journal publications authored by the researchers. Your identity and participation will not be able to be identified in these. If you are in any way uncomfortable with this arrangement, please notify the researchers before you sign the consent form.

What type of information will be sought from me and why is the collection of this information relevant for achieving the research project’s objectives?

In addition to performance data from the Badminton specific fitness test, you will be asked to provide the follow information: Age, Height, Weight, and Number of Years Badminton Playing Experience. For journal publication this information would be reported as a combined value of all participants.

Contact for further information

If you require further information, please contact the principal investigator: Matthew Wylde at matthew_wylde@sportsschool.edu.sg.

Appendix 3

Wylde, M.J., Kumar, B., Low, C.Y. and Callaway, A.J. 2019. Axis specific player load to quantify lower limb biomechanical loading in adolescent Badminton players. *International Journal of Racket Sports Science,* 1(1), 37-44.

Link to Journal Article:

http://eprints.bournemouth.ac.uk/32919/1/Wylde%20et%20al%20Axis-Specific-Player-Load-to-Quantify-Lower-Limb-Biomechanical-Loading-in-Adolescent-Badminton-Players.pdf

Appendix 4

Participant Information Sheet

Project Title: Training Load and Self Reporting of Adolescent Badminton Players

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Invitation

You are being invited to take part in a research project. Before you decide to participate it is important for you to understand why the research is being conducted and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask one of the research team if there is anything that is not clear or if you would like more information.

Background

The use of athlete tracking units that incorporate both global positioning and inertial measurement functionality have become increasingly common and have allowed for quantification of athlete activity across a range of sports. More recently this technology has been used to understand the development of youth athletes in team sports, such as Rugby Union (Read *et al.*, 2016) and Australian Football (Gastin *et al.*, 2017). To date there has been no studies which use this approach to understand the development of youth athletes in individual court based sports, such as Badminton. In addition, studies have demonstrated that athlete self-reporting can be as effective as direct measurement of physical load in senior athletes (Saw *et al.*, 2015). However, there is a lack of studies applying this to a youth athlete population.

Aims

1) To quantify the activity profile of adolescent Badminton players of various age groups and genders.
2) To better understand how self-reporting tools can be used within a youth athlete population.

Duration

Data collection will take part over a 4 to 5 week period at the discretion of your coach.

Why were you chosen?

You have been selected as you are a high level youth Badminton player based in a specialised training environment.

Do I have to take part?

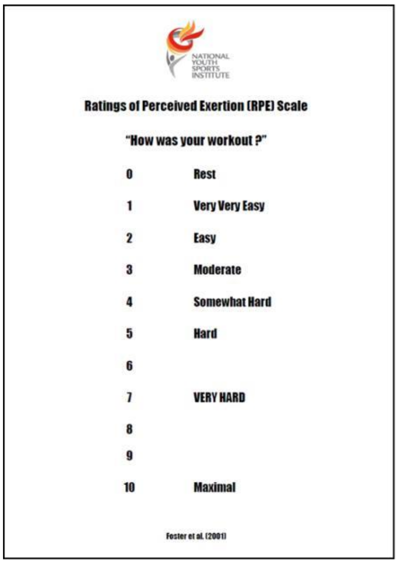
You can decide not to take part at any time. You can refuse further participation during the data collection for any reason. This research investigation is entirely voluntary. If you do decide to take part, you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time without repercussions or affecting any benefits that you are entitled to in any way. You do not have to give a reason.

What do I have to do?

You will be asked to wear a VXSport athlete tracking unit between the shoulder blades in a purpose built harness during training for the duration of the data collection. The dimensions of the unit are 74mm x 47mm x 17mm and the weight is 50gm.

Figure 1 – VXSport Unit and Harness

After each training session you would be required to return the VXSport unit to be charged and for the session data to be downloaded. At this point you would also be requested to provide Ratings of Perceived Exertion, or RPE, (Foster *et al.*, 2001) for the particular training session. You will be asked to differentiate between the overall load of the session (breathlessness) and localised load for your legs (Weston *et al.*, 2015). Prior to the start of the data collection you would be asked to download the free NYSI app. During each morning of the data collection you would be asked to complete a Wellness Questionnaire, where six factors would be rated on a scale of 1 to 5. At the end of the data collection you would need to email these results to be lead researcher.



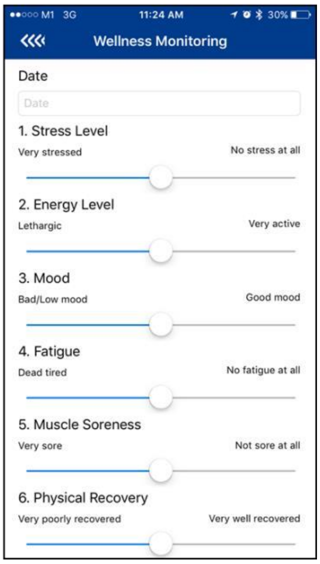


Figure 2 – RPE Scale and Wellness Monitoring Screenshot

What are the possible disadvantages and risks of taking part?

No modification to your training plan is required for this data collection and your coach will be instructed to conduct training as per normal. The positioning of the VXSport unit between the shoulder blades should have minimal effect on movement and should not disrupt training.

What are the possible benefits of taking part?

Information from the data collection will be provided to your coach to better inform training.

Will my taking part in this project be kept confidential?/ What will happen to the results of the research project?

Your identity and any information will always remain confidential and only be known to the researching team. The raw data analysis itself will be stored by the lead researcher at the NYSI Hub @ Woodlands which is located within the Singapore Sports School.

NOTE: The results of this experiment will potentially form part of future scientific journal publications authored by the researchers. Your identity and participation will not be able to be identified in these. If you are in any way uncomfortable with this arrangement, please notify the researchers before you sign the consent form.

What type of information will be sought from me and why is the collection of this information relevant for achieving the research project's objectives?

In addition to the data from the VXSport units, RPE and Wellness scores, you will be asked to provide the follow information: Age, Height and Weight. For journal publication this information would be reported as a combined value of all participants.

Contact for further information

If you require further information, please contact the principal investigator: Matthew Wylde at matthew_wylde@nysi.org.sg

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Appendix 5

Wylde, M.J., Masismadi, N.A., Low, C.Y., Callaway, A.J. and Williams, J.M. 2021. Placement of inertial measurement units in Racket Sports: Perceptions of coaches for IMU use during training and competition. *International Journal of Racket Sports Science*, 3(1), 45-55.

Link to Journal Article:

http://eprints.bournemouth.ac.uk/36068/1/50-Article%20Text-521-1-10-20210915.pdf

Appendix 6

Survey of Racket Sport Coaches and Athletes on the use of Wearable Sensors during Training and Competition

Penyiasatan Atlet dan Jurulatih Raket Sukan mengenai penggunaan Sensor Boleh Dipakai semasa Latihan dan Persaingan

调查：球拍类运动选手及教练在训练和比赛中使用穿戴式传感器

Invitation / Jemputan / 邀请:

You are being invited to take part in a research project. Before you decide to participate it is important for you to understand why the research is being conducted and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask one of the research team if there is anything that is not clear or if you would like more information.

Anda sedang dijemput untuk mengambil bahagian dalam projek penyelidikan. Sebelum anda membuat keputusan untuk mengambil bahagian, penting bagi anda untuk memahami mengapa penyelidikan sedang dijalankan dan penglibatan anda dalam penyelidikan ini. Sila luangkan masa untuk membaca maklumat berikut dengan teliti dan berbincang dengan orang lain jika anda mahu. Sila tanya salah satu pasukan penyelidikan jika ada apa-apa yang tidak jelas atau jika anda ingin maklumat lanjut.

我们诚恳地邀请您参加此研究项目。为了确保您了解此项研究的内容及其重要性，请仔细阅读以下信息，并根据需要与他人讨论。若有任何疑惑，可直接与研究小组联系。

Name, position and contact details of lead researcher / Nama, kedudukan dan butir-butir hubungan penyelidik utama / 研究小组组长的姓名、职位和联系方式:

Mr Matthew Wylde, Head of Performance Analytics, National Youth Sports Institute / Postgraduate Research Student, Bournemouth University - matthew_wylde@nysi.org.sg

Name, position and contact details of supervisors / Nama, kedudukan dan butiran hubungan penyelia / 导师的姓名、职位和联系方式:

Dr Andrew Callaway, Senior Lecturer, Bournemouth University - acallaway@bournemouth.ac.uk
Dr Ian Jones, Associate Professor, Bournemouth University - jonesi@bournemouth.ac.uk
Dr Low Chee Yong, Head of Sport Science, National Youth Sports Institute - low_cheeyong@nysi.org.sg

Background / Latar Belakang / 研究背景

The use of wearable sensors has become increasingly common across elite sport. Such sensors can be worn on various parts of the body to provide information on an athlete's movement (external load) and the response to that movement (internal load). Increasingly the use of sensors can provide insights on the technical and tactical ability of the athletes. While the use of such sensors is prevalent in team based field sports, the use is currently less common in racket sports. The prevalence of wearable sensors in racket sports may be effected by the preference of athletes and coaches regarding their use. However, the preference of racket sport athletes and coaches regarding the use of wearable sensors as a daily monitoring tool during training and competition is currently unclear.

Penggunaan sensor boleh dipakai menjadi semakin popular di seluruh sukan elit. Sensor sedemikian boleh dipakai di pelbagai bahagian badan untuk memberi maklumat mengenai pergerakan atlet (beban luaran) dan tindak balas terhadap pergerakan itu (beban dalaman). Penggunaan sensor semakin dapat memberikan pandangan tentang keupayaan teknis dan taktik para atlet. Walaupun penggunaan sensor sedemikian lazim dalam sukan berasaskan pasukan, penggunaan kini kurang biasa dalam sukan raket. Kebarangkalian sensor yang boleh dipakai dalam sukan raket boleh terjejas oleh keutamaanatlet dan jurulatih mengenai penggunaannya. Walau bagaimanapun, keutamaan atlet dan jurulatih sukan raket mengenai penggunaan sensor sebagai alat pemantauan harian semasa latihan dan persaingan tidak jelas.

在竞技运动中，穿戴式传感器的使用日益普遍。这种传感器可穿戴在身体的各个部位，以提供有关运动员的动作（外部负荷）和机能反映（内部负荷）的信息，进而监察运动员的竞技战术能力。球类运动及综合运动训练中普遍使用这种传感器，但球拍类运动方面目前的使用较少。作为日常训练以及比赛时的运动监测，球拍类运动选手及教练对使用穿戴式传感器的意愿尚不明确。

Aims / Tujuan / 目的:

The aim of this study is to survey racket sports athletes and coaches (Badminton, Squash, Table Tennis and Tennis) to understand their preference on:

1) the use of wearable sensors worn at various positions of the arm, leg and body;
2) the maximum number of wearable sensors they would wear/allow their athletes to wear;
3) the use of wearable sensors during training and/or competition.

Tujuan kajian ini adalah untuk meninjau atlet raket dan jurulatih sukan (Badminton, Skuasy, Tenis Meja dan Tenis) untuk memahami keutamaan mereka mengenai:

1) penggunaan sensor dipakai pada pelbagai kedudukan lengan, kaki dan badan;
2) bilangan maksimum sensor boleh dipakai yang mereka mampu pakai / membenarkan atlet mereka memakai;
3) penggunaan sensor yboleh dipakai semasa latihan dan / atau persaingan.

此项研究的目的在于了解球拍类运动选手和教练（羽毛球、壁球、乒乓球和网球）对以下几个方面的意见：

1）把传感器穿戴在手臂、腿部和身体等部位；
2）愿意穿戴的数量；
3）在训练和/或比赛中使用穿戴式传感器的意愿。

What do I have to do / Apa yang perlu saya buat / 我需要做什么?

You will be asked to complete the following survey regarding your preference on the use of wearable sensors by yourself or by athletes you are currently coaching. All information provided is anonymous and confidential, with no personal information being collected.

Anda akan diminta untuk melengkapkan kaji selidik berikut mengenai keutamaan anda mengenai penggunaan sensor boleh dipakai oleh diri sendiri atau oleh atlit yang sedang anda melatih. Semua maklumat yang diberikan adalah tanpa nama dan sulit, tiada maklumat peribadi yang dikumpulkan.

请完成以下关于使用穿戴式传感器意愿的调查。您所提供的所有信息都将被严格保密并以匿名显示。另外，此项调查将不会收集任何个人资料。

Provision of Consent / Pemberian Persetujuan / 同意书

By submitting your response to the survey you are providing your consent for the information to be collected as part of this research study. As the submission is anonymous, it is not possible to withdraw your response after submission.

Dengan mengemukakan respons anda kepada kaji selidik, anda memberikan persetujuan anda untuk maklumat dikumpulkan sebagai sebahagian daripada kajian penyelidikan ini. Oleh kerana penyerahan itu tanpa nama, tiada kemungkinan untuk menarik balik tanggapan anda selepas penyerahan.

参与调查意味着您同意参与此项研究。倘若您选择以匿名显示，就将无法撤回您所提交的信息。

Contact for further information / Hubungi untuk maklumat lanjut / 获取更多信息

If you require any further information, please feel free to contact Mr Matthew Wylde at matthew_wylde@nysi.org.sg

In case of complaint regarding the data collection please contact Professor Lee Miles (Acting Deputy Director Dean for Research and Professional Practice, Bournemouth University) via researchgovernance@bournemouth.ac.uk.

Sekiranya anda memerlukan sebarang maklumat lanjut, sila hubungi Encik Matthew Wylde di matthew_wylde@nysi.org.sg

Dalam kes aduan mengenai pengumpulan data sila hubungi Profesor Lee Miles (Pemangku Timbalan Pengarah Dekan Penyelidikan dan Profesional, Universiti Bournemouth) melalui researchgovernance@bournemouth.ac.uk.

欲了解更多详情，请电邮至 matthew_wylde@nysi.org.sg 与 Matthew Wylde 先生联系。

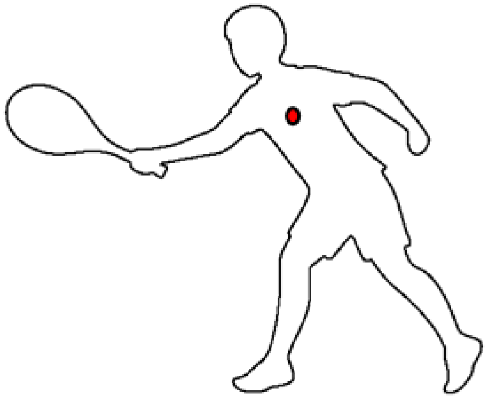
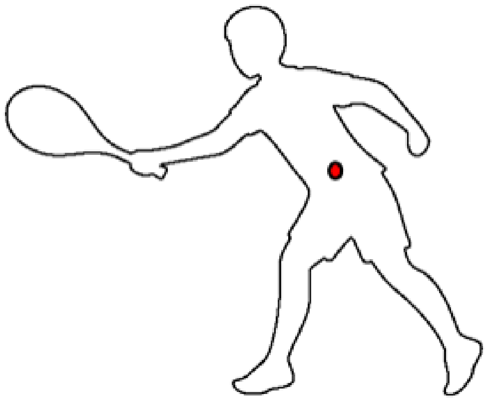
若有任何不满，请电邮至 researchgovernance@bournemouth.ac.uk 与 Lee Miles 教授（伯恩茅斯大学研究与专业实践代理副主任）联系。

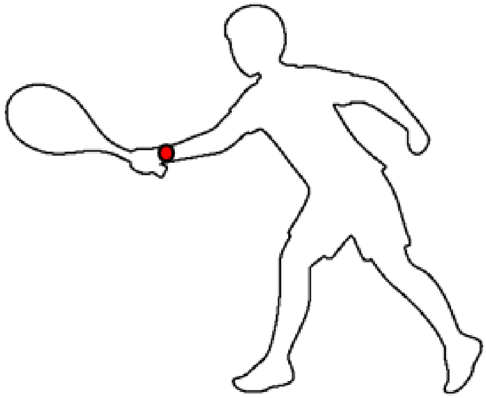
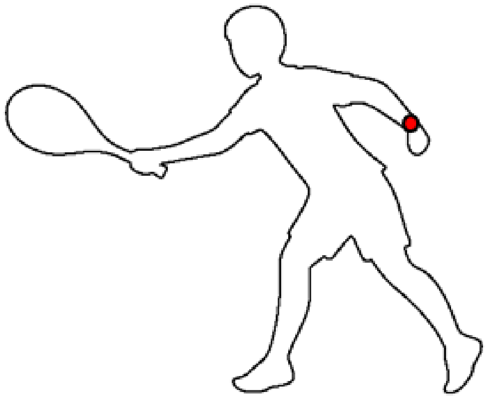
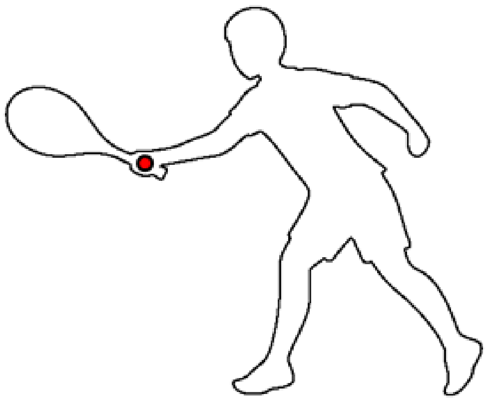
Survey / Ukur / 调查

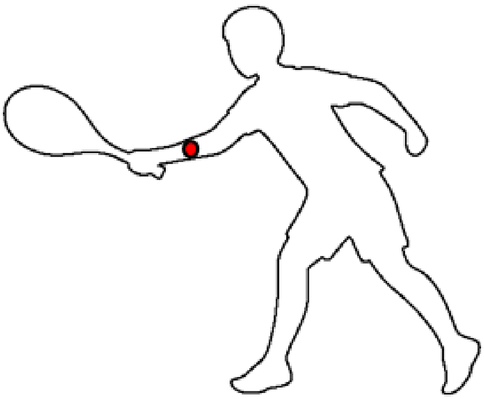
Questions / Soalan /问题	**Options / Pilihan / 选项**
Are you 21 years or above? Adakah anda 21 tahun ke atas? 您是否年满 21 岁？	Yes / Ya / 是 No (if “No” then the participant will be informed that they cannot continue with the survey) Tidak (jika

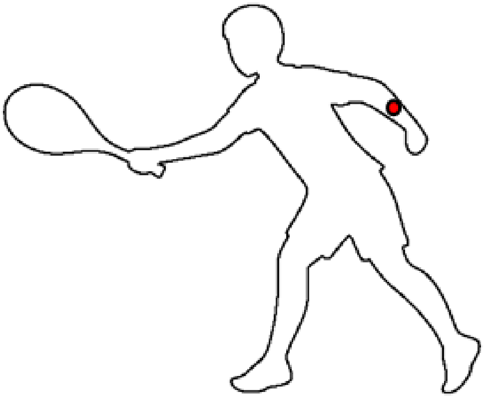
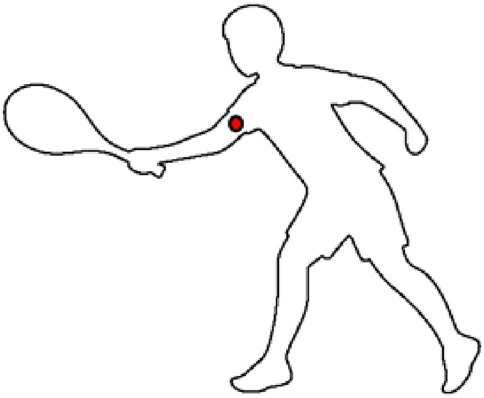
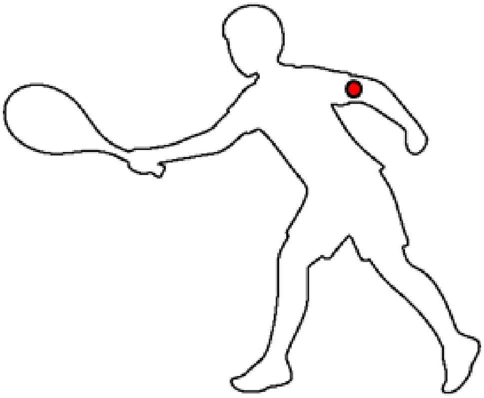
	"Tidak" maka peserta akan dimaklumkan bahawa mereka tidak dapat meneruskan kajian) 否（未满 21 岁者将无法参与调查）
Do you consent to your anonymous response being used in this study? (Note: Due to the anonymous nature of the survey, it will not be possible to delete your response once submitted.) Adakah anda bersetuju dengan tindak balas anonim anda yang digunakan dalam kajian ini? (Nota: Oleh sebab sifat tinjauan tanpa nama, tidak akan dapat memadamkan respons anda sebaik sahaja dihantar.) 您是否同意在这项研究中使用匿名回复？ （注意： 倘若您选择以匿名显示，就将无法撤回您所提交的信息。）	Yes / Ya / 是 No / Tidak /否
Are You An Athlete or Coach? Adakah Anda Seorang Atlet atau Jurulatih? 您是运动员还是教练？	Athlete / Atlet /运动员 Coach / Jurulatih / 教练
What Sport Do You Play/Coach? Apakah Sukan Anda Main / Melatih? 您从事 /指导哪项运动？	Badminton / 羽毛球 Squash / Skuasy /壁球 Table Tennis / Tenis Meja /乒乓球 Tennis / Tenis / 网球 Other / Lain-lain/ 其他
What Level Do You Play/Coach? Tahap Apakah Anda Main / Melatih? 您所从事/指导的运动属于什么级别？	Elite/ 竞技项目 Youth Development / Pembangunan Belia / 青年计划 Club / Kelab / 俱乐部 School / Sekolah / 学校
In Which Country Do You Reside? Di Negara manakah anda tinggal?	

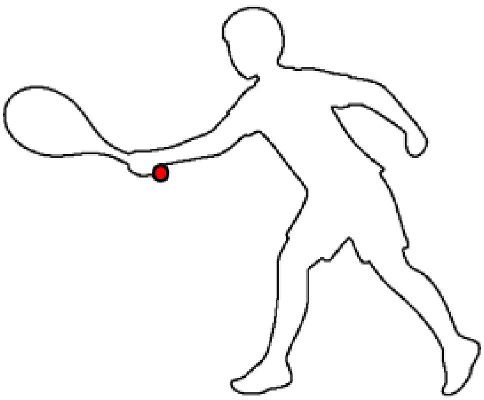
您居住在哪个国家？	
Would you be willing for yourself/your athlete to wear a sensor during training? Adakah anda bersedia untuk diri sendiri / atlet anda memakai sensor semasa latihan? 训练时，您是否愿意为自己/您的运动员佩戴传感器？	Yes / Ya / 是 No / Tidak /否
Would you be willing for yourself/your athlete to wear a sensor during competition? Adakah anda bersedia untuk diri sendiri / atlit anda memakai sensor semasa persaingan? 比赛时，您是否愿意为自己/您的运动员佩戴传感器？	Yes / Ya / 是 No / Tidak /否
What is maximum number of sensors you would be comfortable with yourself/your athlete wearing during training? Berapakah bilangan maksimum sensor yang anda selesa dengan diri anda / atlet anda memakai semasa latihan? 训练时，您愿意为自己/您的运动员佩戴最多___个传感器。	
What is maximum number of sensors you would be comfortable with yourself/your athlete wearing during competition? Berapakah bilangan maksimum sensor yang anda selesa dengan diri anda / atlet anda memakai semasa persaingan? 比赛时，您愿意为自己/您的运动员佩戴最多___个传感器。	

Upper back / Atas belakang / 背部 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Lower back / Balik belakang /腰部 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Wrist (dominant) / Pergelangan tangan (dominan) / 手腕（惯用）	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否

	
Wrist (non-dominant) / Pergelangan tangan (tidak dominan) /手腕（非惯用） 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Hand (dominant) / Tangan (dominan) / 手（惯用） 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否

Hand (non-dominant) / Tangan (tidak dominan) / 手（非惯用） 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Lower-arm (dominant) / Lengan bawah (dominan) / 前臂（惯用） 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Lower-arm (non-dominant) / Lengan bawah (tidak dominan) / 前臂（非惯用）	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否

	
Upper-arm (dominant) / Lengan atas (dominan) / 上臂（惯用） 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Upper-arm (non-dominant) / Lengan atas (tidak dominan) /上臂（非惯用） 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否

Lower Leg / Buku lali / 脚踝 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Shoe / Kasut / 鞋子 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak / 否
Racket handle / Pemegang raket / 球拍手柄 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak /否

Racket head / Kepala raket / 球拍头 	Yes in training / Ya dalam latihan / 是的，在训练中 Yes in competition / Ya dalam persaingan /是的，在比赛中 No / Tidak /否

END / AKHIRNYA / 完

Appendix 7

Wylde, M.J., Callaway, A.J., Williams, J.M., Yap, J., Leow, S. and Low, C.Y. 2022. Limb specific load and asymmetry measurement to discriminate between athletes with and without unilateral or bilateral lower limb injury history. *Physical Therapy in Sport,* Under Review.

Limb specific training magnitude and asymmetry to discriminate between athletes with and without unilateral or bilateral injury history

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LIMB SPECIFIC TRAINING MAGNITUDE AND ASYMMETRY MEASUREMENT TO DISCRIMINATE BETWEEN ATHLETES WITH AND WITHOUT UNILATERAL OR BILATERAL LOWER LIMB INJURY HISTORY

Abstract

Objectives: This study investigates the use of tibia-mounted IMUs as an alternative to upper trunk-mounted IMUs for assessing lower limb training magnitudes and asymmetries in Badminton players.

Design: Cross-Sectional Study.

Setting: Youth athlete training environment.

Participants: Thirty-three adolescent Badminton players, grouped based on injury history (non-injured = 19, bilateral = 6, unilateral = 8).

Main Outcome Measures: Players wore 1 upper trunk-mounted and 2 tibia-mounted IMUs during simulated match-play. Modified vector magnitudes were assessed to identify if the IMUs can discriminate between injury history groups to assess the device location sensitivity, determine if players exhibit movement asymmetry within the sport, and explore if asymmetries exist within groups with injury history.

Results: Upper trunk-mounted IMUs could not distinguish between injury history groups. Statistically significant asymmetries were observed in the non-injured group, however these we below the 10% threshold for clinical asymmetry. No significant asymmetries were observed in the bilaterally injured group, while statistically significant asymmetries were observed in the unilaterally injured group, which were above the 10% threshold for clinical asymmetry.

Conclusion: These results suggest that direct limb specific IMU measurement offers a method to suitably assess training magnitudes and asymmetry within a sporting performance, rather than isolated non-sport specific testing.

Keywords

Limb Symmetry Index; Vector Magnitude; Acceleration; Inertial Measurement Unit.

Introduction

Badminton is a court-based racket sport characterised by periods of high intensity activity interspersed with short rests (Alcock and Cable, 2009). In elite Badminton players, injuries have been measured at 5.04 injuries per 1000 playing hours, with lower limb injuries accounted for 43% of all injuries sustained over a 1-year period (Yung *et al.*, 2007). Furthermore, 64% of injuries recorded in youth Badminton players were soft-tissue sprains and strains, with knee injuries accounting for 42% of lower limb injuries (Goh *et al.*, 2013).

In addition to lower limb injuries, the presence of asymmetry between the lower limbs is associated with poorer jump performance, change of direction speed and agility as well as being linked to injury risk (Hoffman *et al.*, 2007; Bell *et al.*, 2014; Steild-Muller *et al.*, 2018; Madruga-Parera *et al.*, 2019; Helme *et al.*, 2021). The limb symmetry index is a frequently used metric in sports medicine (Engalen-van Melick *et al.*, 2013; Abrams *et al.*, 2014) and is most commonly used as a rehabilitation target for those recovering from knee ligament injuries (Almangoush and Herrington, 2014). To that end, the value of <10% limb asymmetry is particularly common as a return to sport criterion (Schmitt *et al.*, 2012; Abrams *et al.*, 2014). This criterion has been used for strength (Brown *et al.*, 2020) and functional performance testing such as hopping distance (Almangoush and Herrington, 2014).

One challenge to the use of specific tests of limb asymmetry, is whether it truly represents the ability to achieve the underlying sporting function. For example, a triple hop for distance test is not an exact representation of the functional requirements for each specific sport. Therefore, it is possible that these specific tests of limb asymmetry may mask underlying deficits in limb function during more sport specific movements. To this end, a method of measuring limb symmetry during actual play may offer new insights into limb asymmetry, especially when exploring injury risk. However, in order to achieve this, it is imperative to understand the normal limb asymmetry in a particular sport, as a high number of sports pertain to asymmetry, i.e. racket sports. Once baseline asymmetry can be established, this serves as a platform to determine whether limb asymmetry, such as <10%, is truly meaningful or just as a consequence of the asymmetrical sport.

Monitoring the activity profiles of athletes during training or competition is important for determining whether athletes are adapting to a training programme, understanding the need for recovery and attempting to reduce injury risks (Bourdon *et al.*, 2017). The use of wearable micro-technology, such as inertial measurement units (IMUs), has become an important tool for monitoring activity profiles within training programmes. IMUs are light, portable, inexpensive, easy to set up and allow for rapid evaluation of a large number of athletes (Picerno *et al.*, 2011). Tri-axial acceleration data from IMUs can be combined to produce the parameter coined ‘Player Load’ (Boyd *et al.*, 2011). ‘Player Load’ has been used across a range of team sports (Fox *et al.*, 2018) and court-based sports, including Badminton (Abdullahi *et al.*, 2019; Wylde *et al.*, 2019).

While the use of terms such as “workload”, “training load” and “Player Load” are common within both the scientific literature and applied setting, these terms may be inappropriate and potentially confusing given the lack of clarity regarding what is being measured (Staunton *et al.*, 2021). The terms “work” and “load” have prescribed units of measurement under the Système International d'Unités (SI), being joule (J) and newton (N) respectively. However, as “training load” is rarely reported using the SI prescribed units, the use of these terms in scientific literature should be avoided. The term “intensity” has been suggested for describing how hard somebody is exercising to avoid misuse of mechanical constructs such as ‘load’ and ‘work’ (Staunton *et al.*, 2021). However, for accelerometer derived measurements such as “Player Load”, we suggest that the term “training magnitude” may be more appropriate, as this denotes the size of the demand being placed on the athlete during training.

Common practice for the measurement of training magnitudes is to use upper trunk-mounted IMUs, however, this device location has been found to be poor in estimating vertical acceleration of the centre of gravity and thoracic segment, and for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018), which would be necessary to determine any asymmetries. This is perhaps due to the IMU being positioned far from the point of ground contact, therefore mechanical energy is absorbed and dissipated through the joints and body tissues between the foot and the IMU (Derrick *et al.*, 1998; Glassbrook *et al.*, 2020). This demonstrates that the location of IMUs are important relative to the purpose to which they are being used.

Given the lower limb injury prevalence and potential performance implications of lower limb asymmetry in racket sports (Madruga-Parera *et al.*, 2019), a more direct measure may be required to monitor lower limb training magnitudes to assess movement asymmetry. Previously, it has been shown that lower limb-mounted IMUs were able to quantify training magnitudes more directly that those mounted on the upper body and measure asymmetry of running in Rugby players (Glassbrook *et al.*, 2020). Tibia-mounted IMUs have been found to provide good-to-excellent reliability for measurement of training magnitudes during Football (Soccer) specific acceleration-deceleration, ‘plant and cut’ and change of direction tasks (Burland *et al.*, 2021). Lower limb-mounted IMUs may therefore provide a more direct measure of lower limb training magnitudes and assessment of movement asymmetry, which may have potential implications for injury management.

With the potential benefits of using lower limb-mounted IMUs for the management of injury risk and movement asymmetries, coupled with the susceptibility of the Badminton playing population to lower limb injuries and propensity for lower limb asymmetry, further study is warranted to assess the application of this method within Badminton. The aims of this study were to (1) assess if training magnitudes calculated from upper trunk- or tibia-mounted IMUs can discriminate between players with no, uni-, bi-lateral injury history, (2) determine if Badminton players exhibit movement asymmetry during simulated match play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history.

Methods

This study utilised a cross sectional, observational study design. All data were collected during 90 minutes of simulated match-play within the high-performance centre during a normal 3-hour badminton training session. The study was approved by the Singapore Sport Institute Institutional Review Board. Informed assent was obtained from all participants and informed consent was obtained from each participant's parent/legal guardian.

The 33 participants for this study (14 female and 19 male) were recruited from adolescent Badminton athletes based at a dedicated high-performance youth training environment (Age: 14.4 ± 1.2 y, Height: 1.65 ± 0.10 m, Mass: 54.6 ± 9.4 kg, Playing Experience: 7.3 ± 1.7 y). The sample size was determined using data from a study of asymmetry in youth Tennis players Madruga-Parera *et al.* (2019), where a mean and standard deviation of the percentage difference between limbs was calculated along with an alpha of 0.01, beta 80% and group allocation ration of 1:3. In order to be included, athletes needed to be cleared to participate in the sport by a certified sports physiotherapist at both the stage of consent and data collection. Participants were allocated to one of three groups. Grouping was based on their injury history within the previous 2 years, with the *non-injured group* being athletes with no injury history, the *unilaterally injured group* being athletes with an injury to one lower limb and the *bilaterally injured group* being athletes with an injury to both lower limbs. For purpose of this study, injury was defined as any physical complaint or manifestation sustained by a player that results from a match or training (Pluim *et al.*, 2009), which resulted in the athlete being unable to take part in normal training by a certified sports physiotherapist for 3 consecutive training sessions. Post data collection, each athlete was asked to complete a questionnaire reporting any lower limb injuries sustained during the previous 2 years.

During the data collection, each athlete wore three VXSport (Visuallex Sport International, Lower Hutt, New Zealand) log units (dimensions: 74mm x 47mm x 17mm, weight: 50g). The upper trunk-mounted unit was worn between the scapulae in a purpose-built harness, with the remaining two units secured on the skin over the left and right mid-tibia using adhesive tape. The VX Sport system has been found to possess both high intra-system (CV% range 1 to 5.1; ICC range 0.958 to 0.996) and inter-system reliability compared with the Catapult Optimeye S5 system (CV% range 2.8 to 7.3; ICC range 0.785 to 0.970) for the measurement of Badminton specific movements (Wylde *et al.*, 2018). Acceleration data were recorded 100Hz. Prior to the commencement of the data collection the athletes took part in a standardised team warm-up as prescribed the coach. Training sessions lasted 90 minutes and consisted of simulated Badminton match-play with multiple matches of up to 3 sets of 21 points. During the simulated match-play the athletes were matched by the coach based on age, gender and playing ability.

Using the acceleration data, the appropriate filtering frequency and residual analysis was conducted (Winter, 2009) on a sample of five participants. Based on the residual analysis the raw data were filtered using a bidirectional 3rd order low pass Butterworth filter with cut-off frequency of 7Hz for the scapulae units, and 6Hz for the tibia units, and mean centred in Matlab (MathWorks, Natick, MA, USA).

Training magnitude was calculated using a modified vector magnitude (VM) calculation, being the square root of the sum of the acceleration squared (Boyd *et al.*, 2011) (Equation 1) and the training magnitudes for the vertical, antero-posterior and medio-lateral axis were also calculated (Equation 2). To aid comparison, the training magnitudes for the tibia-mounted IMUs were normalised against the training magnitudes from the upper trunk-mounted IMU.

$$Total\,VM = \sqrt{\frac{(ax_1 - ax_{-1})^2 + (ay_1 - ay_{-1})^2 + (az_1 - az_{-1})^2}{100}}$$

Equation 1: Modified Vector Magnitude calculation

$$Vertical\,VM = \sqrt{\frac{(az_1 - az_{-1})^2}{100}} \qquad Antero - Posterior\,VM = \sqrt{\frac{(ay_1 - ay_{-1})^2}{100}} \qquad Medio - Lateral\,VM = \sqrt{\frac{(ax_1 - ax_{-1})^2}{100}}$$

Equation 2: Vertical, Antero-Posterior, Medio-Lateral Vector Magnitude calculations

Asymmetries between the non-dominant and dominant leg and the injured and non-injured leg were calculated using the following equation (Schitlz *et al.*, 2009).

$$Asymmetry\ = (1 - \frac{NDL}{DL}) x\ 100$$

Equation 3: Non-Dominant Leg (NDL) vs Dominant Leg (DL) Asymmetry

$$Asymmetry\ = (1 - \frac{IL}{NIL}) x\ 100$$

Equation 4: Injured Leg (IL) vs Non-Injured Leg (NIL) Asymmetry

The normality of the data was assessed using the Shapiro-Wilk test, with data found to be normally distributed. Differences between the dominant and non-dominant legs, injured and non-injured legs and between the three athlete sub-groups (non-injured, bilaterally injured and unilaterally injured) were calculated using independent t-tests, analysis of variance (ANOVA) tests, both with significance set at ≤0.01 to accommodate for multiple testing, and Cohen's Effect Sizes (Cohen, 1988) with modified interpretative descriptors (Tan *et al.*, 2009): <0.20 = "trivial", 0.20 to 0.59 = "small", 0.60 to 1.19 = "moderate", 1.20 to 1.99 = "large", and >2.00 = "very large".

Results

All 33 athletes completed 90 minutes of data collection with no dropouts or data fidelity errors. Training magnitudes calculated from the upper trunk-mounted IMU demonstrated non-significant differences with trivial to small effect sizes between the non-injured and bilaterally injured athlete groups (Table 1). There were moderate effect sizes observed between the non-injured and unilaterally injured groups for total VM and axis specific VM and between the bilaterally and unilaterally injured groups for medio-lateral VM. However, these differences were outside the threshold of statistical significance (≤0.01) set for this study.

Within the non-injured group, significantly higher tibia magnitudes were observed in the non-dominant leg on the antero-posterior and vertical axis, with moderate and small effect sizes respectively (Tables 2 and 3). The observed asymmetries ranged from -4% to 7% between the dominant and non-dominant legs (see Table 4).

Within the bilaterally injured group no significant differences were observed between the non-dominant and dominant leg across any of the axis, with trivial or small effect sizes recorded for each (Tables 2 and 3). In all cases the observed asymmetries were within +/- 3% between the dominant and non-dominant legs (see Table 4).

Within the unilaterally injured group significantly higher tibia magnitudes were observed on the non-injured leg for vertical VM, with moderate effect sizes for total VM and all axis specific VM (Tables 2 and 3). The asymmetries recorded between the injured and non-injured leg were between 10% and 13%, with these higher loads recorded on the non-injured leg (see Table 4).

In the comparison of tibia asymmetries between the non-injured and bilaterally injured groups, no significant differences were observed but moderate effect sizes were evident for total VM and vertical VM (see Table 4). Between the non-injured and unilaterally injured groups significant differences were observed for antero-posterior VM and vertical VM (see Table 3). A large effect size was recorded for total VM, with very large effects sizes recorded for antero-posterior VM and vertical VM. Between the bilaterally injured and unilaterally injured groups no significant differences were observed, but moderate to large effect sizes were determined for all variables (see Table 4).

Inspection of the individual athlete asymmetries demonstrates that in the non-injured athlete group the majority of athletes recorded higher training magnitudes in the non-dominant leg on the antero-posterior axis and vertical axis (see Figure 1). However, for the medio-lateral axis higher training magnitudes were predominately recorded on the dominant leg. For the bilaterally injured athletes, higher training magnitudes were predominately recorded on the dominant leg for the medio-lateral and vertical axis (see Figure 2). By contract, the unilaterally injured athletes all recorded higher training magnitudes on the non-injured leg for total VM, medio-lateral VM, antero-posterior VM and vertical VM (see Figure 3).

Discussion

The aims of this work were to (1) assess if training magnitude calculated from upper trunk- or tibia-mounted IMUs can discriminate between players with no, uni-, bi-lateral injury history, (2) determine if Badminton players exhibit movement asymmetry during simulated match play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history.

Assessment of training magnitudes between the three groups using the upper trunk-mounted IMUs revealed no significant differences, demonstrating an inability to adequately distinguish between the groups. Upper trunk-mounted IMUs appear limited for the assessment of lower limb training magnitudes, which is consistent with the study of Rugby Union players, where upper trunk-mounted IMUs were found to be unsuitable for measuring vertical ground reaction forces during running (Edwards *et al.*, 2018). This also supports findings from within Badminton, where training magnitudes calculated from upper trunk-mounted IMUs were found to be poorly correlated with differential ratings of perceived exertion (RPE) for the lower limbs (Wylde *et al.*, 2019). As upper trunk-mounted IMUs are positioned far from the point of ground contact, the mechanical energy is absorbed and dissipated through the joints and body tissues regarding the validity of the training load measures (Derrick *et al.*, 1998; Glassbrook *et al.*, 2020). In addition, the elasticised harness used the mount the IMU to the upper trunk is a potential source of extra movement of the IMU during high intensity activities (Edwards *et al.*, 2018). Given the limitations of upper trunk-mounted IMUs for assessing lower limb training magnitudes, there is the potential for greater insights to be derived from the use of additional tibia-mounted IMUs.

Lower limb-mounted IMUs have been found to be a valid tool for detecting asymmetries during sport match-play (Glassbrook *et al.*, 2020) and therefore provide a potential means of distinguishing between athlete groups based on injury history. Using training magnitudes calculated from the tibia-mounted IMUs as a means of comparison, significant differences were observed between the dominant and non-dominant lower limbs in the non-injured group, for antero-posterior VM and vertical VM, with small to moderate effect sizes. The antero-posterior and vertical VM were higher on the non-dominant leg. While the movement asymmetries were comparatively small (between -4% and 7%) and below the 10% threshold for clinically significant asymmetry (Schmitt *et al.*, 2012; Abrams *et al.*, 2014;), these findings appear contrary to evidence of structural asymmetry in the lower limbs of Badminton players (Bravo-Sanchez *et al.*, 2019) and movement asymmetry in lunge tasks (Nadzalan *et al.*, 2017), where higher values were recorded in the dominant leg. In a study of landing strategies in male Badminton players, it was found that the backhand jump smash resulted in significantly greater vertical ground reaction forces, time to peak acceleration and 50ms impulse compared to target striking and court-based footwork (Hung *et al.*, 2020). However, there were no significant differences in the horizontal ground reaction forces between the three movements. In this study all participants were right-handed and while the take off for the jump smash was from both feet, the peak accelerations were recorded on the left-side (non-dominant) foot. It is therefore likely that the decelerations recorded from jump smash landings, and similar high impact activities, where the athlete lands on the non-dominant foot, contributes to greater training magnitudes being recorded in the non-dominant leg on the antero-posterior and vertical axis but not on the medio-lateral axis. While these movements create high ground reaction forces, and by extension accelerometer derived training magnitudes, other movements such as lunges, which account for 15% of movements in Badminton (Kuntze *et al.*, 2009), may contribute to the structural asymmetries which have been observed. This may be due to the eccentric component of the movement (Fu *et al.*, 2017) which contributes to greater thickness of the muscle architecture in the dominant lower limb compared to the non-dominant limb but would not create large ground reaction forces (Bravo-Sanchez *et al.*, 2019).

While significant asymmetries in antero-posterior VM and vertical VM were observed towards the non-dominant leg in the non-injured group, these were not present in bilaterally injured group, with significantly lower asymmetry observed for vertical VM in the bilaterally injured group compared to the non-injured group. Given that landing from a jump smash produce high ground reaction forces (Hung *et al.*, 2020), and by extension accelerometer derived training magnitudes, it is possible that the bilaterally injured group have developed modified movement strategies to limit the impact of these movements. In a study of Badminton players with and without knee pain, the injured group used reduced knee and upper trunk motions to complete backhand lunge tasks, with the injured players adopting a smaller centre of mass and centre of pressure displacement during to reduce the load on the supporting limb (Lin *et al.*, 2015). It is likely that the athletes in the bilaterally injured group have adopted similar strategies to reduce training magnitude during high impact Badminton movements, such as the jump smash, which have resulted in lower vertical loads on the non-dominant leg.

In the unilaterally injured group, significant differences were observed on normalised vertical VM, while moderate effect sizes were observed for total VM, antero-posterior VM and vertical VM, with higher training magnitudes recorded on the non-injured leg in all cases. These asymmetries were between 10% and 13%, which are equal or above the 10% threshold commonly used for clinical decision making (Schmitt *et al.*, 2012; Abrams *et al.*, 2014), and were significantly higher than the non-injured groups for antero-posterior VM and vertical VM. The mechanisms behind such alterations in limb specific training load are not immediately identifiable from the current study. As lower limb asymmetry negatively vertical jump performance and change of direction speed in youth racket sport players (Madruga-Parera *et al.*, 2019), the clinically significant asymmetry observed in the unilaterally injured group suggests that performance of athletes in this group may be compromised.

The results of this study demonstrate that, compared to non-injured and bilaterally injured players, those with unilateral low limb injury had asymmetries of between 11-16%. This finding is novel of the literature due to the tibia training magnitude symmetry being studied for the first time in Badminton players. It seems likely that Badminton players demonstrate less cumulative training magnitudes through their injured limb compared to their non-injured limb. Previous research has demonstrated ongoing limb asymmetry following unilateral limb injury. It is possible these alterations serve as a protective strategy to reduce the load on the injured limb therefore minimising the provocation of pain. Conversely, these alterations may represent sub-optimal recovery from the injury where lingering deficits in unilateral limb performance remain. This may be due to a well-documented response to pain where the body seeks to minimise the provocation of pain and protect the injured area (Henriksen *et al*., 2010; Ward, 2014). Such responses to pain and injury have been documented across other body regions (Williams *et al.*, 2010) and this adaptive response may serve as a mechanism to maintain function (in this case playing Badminton) whilst avoiding provocation and irritation of the injury. An alternate hypothesis to explain these findings suggests that this difference is a lingering impairment of function. It is well documented that following injury to a limb, widespread changes to the function of the limb are witnessed and these are known to remain, even after resolution of the pain (Ward, 2014). In this case, targeting this sub-optimal function may prove beneficial to close the symmetry gap. However, no pain was reported during or after testing questioning the hypothesis around the avoidance of pain provocation.

The values of injured limb training magnitudes are very similar to the values of limb training magnitudes demonstrated in the non-injured group. This suggests that the injured limb was being used as much as those limbs in the non-injured group. Therefore, based on our data the asymmetry seems to be driven by an increase in limb training magnitudes from the non-injured leg. This represents a truly novel finding and it is not immediate clear why such a difference was observed. It is possible that the above explanations hold true, in that there is still protection, or a lingering impairment and future investigations are needed to explore the cause and effect relationship through prospective work.

In current practice, a common assessment of asymmetries of injured and non-injured athlete populations involves the use of vertical jump (Impellizzeri *et al.*, 2007) or counter-movement jump protocols (Hart *et al.*, 2019). However, there is no consensus on the use of such tests in the clinical setting to monitor athletes recovering for lower limb injury (Lynch *et al.*, 2015). In addition, these methods do not account for the on court/field based movements during training or competition (Glassbrook *et al.*, 2020) and potentially takes athletes away from training for assessment. The use of tibia-mounted IMUs therefore provide a tool for practitioners to assess lower limb asymmetry for sport specific movements in a normal training environment. Athlete specific training magnitude asymmetries can be gathered from tibia-mounted IMUs during training with little encumbrance the athletes' movement. Information gathered from the tibia-mounted IMUs would provide a baseline for each athlete's pre-injury training magnitude pattern. In instances of injury, the baseline measure would provide practitioners with a benchmark to assess how close the athlete has returned to the pre-injury training magnitude pattern during the rehabilitation process. This would complement existing jump based asymmetry protocols and provide a sport specific assessment of the athlete's loading pattern and potentially a more accurate method of assessing the athlete's ability to return to performance.

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Table 1 – Comparison of axis specific vector magnitudes from the upper trunk-mounted IMUs between non-injured, bilaterally injured and unilaterally injured athlete populations

Measure (Upper trunk-mounted IMU)	Non Injured (N=19) Mean (SD)	Bilaterally Injured (N=6) Mean (SD	Unilaterally Injured (N=8) Mean (SD	Non Injured vs. Bilaterally Injured		Non Injured vs. Unilaterally Injured		Bilaterally Injured vs. Unilaterally Injured		Between All Groups
				P Value	Effect Size	P Value	Effect Size	P Value	Effect Size	ANOVA P Value
Total VM	22978.8 (4689.9)	24054.7 (5573.7)	26806.6 (4554.3)	0.64	-0.22 *Small*	0.06	-0.83 *Moderate*	0.33	-0.56 *Small*	0.19
Medio-Lateral VM	10353.9 (2053.2)	10672.2 (2058.7)	12087.8 (1986.6)	0.74	-0.16 *Trivial*	0.05	-0.86 *Moderate*	0.22	-0.71 *Moderate*	0.15
Antero-Posterior VM	10625.9 (2507.4)	11062.4 (3478.9)	12322.1 (2184.0)	0.74	-0.16 *Trivial*	0.11	-0.71 *Moderate*	0.42	-0.46 *Small*	0.32
Vertical VM	13673.4 (2893.4)	14532.2 (3141.7)	16047.5 (3037.7)	0.54	-0.29 *Small*	0.07	-0.82 *Moderate*	0.38	-0.50 *Small*	0.18

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

Table 2 – Comparison of asymmetry within non-injured, bilaterally injured and unilaterally injured athlete populations

Measure (Tibia-mounted IMUs)	**Non-injured (N=19)**					**Bilaterally Injured (N=6)**					**Unilaterally Injured (N=8)**				
	Non Dominant - Mean (SD)	**Dominant - Mean (SD)**	**%**	**P Value**	**Effect Size**	**Non Dominant - Mean (SD)**	**Dominant - Mean (SD)**	**%**	**P Value**	**Effect Size**	**Injured - Mean (SD)**	**Non Injured - Mean (SD)**	**%**	**P Value**	**Effect Size**
Total VM	36142.7 (6709.6)	35612.9 (6971.9)	1	0.14	0.08 *Trivial*	36743.2 (7014.8)	36861.8 (5426.9)	0	0.89	-0.02 *Trivial*	36039.8 (6582.9)	40957.6 (5756.9)	-14	0.05	-0.80 *Moderate*
Medio-Lateral VM	18342.9 (3436.9)	19103.5 (3877.1)	-4	0.06	-0.21 *Small*	18977.0 (3856.6)	19351.2 (2613.5)	-2	0.65	-0.11 *Trivial*	18210.0 (3623.2)	20809.5 (2375.7)	-14	0.11	-0.86 *Moderate*
Antero-Posterior VM	16817.2 (2991.9)	15866.1 (3176.5)	6	**<0.001***	0.31 *Small*	16987.2 (3034.9)	16537.5 (2546.1)	3	0.50	0.16 *Trivial*	16448.4 (3162.2)	19051.8 (2951.1)	-16	0.05	-0.86 *Moderate*
Vertical VM	19035.9 (3830.9)	18386.7 (3738.2)	3	**0.003***	0.17 *Trivial*	19154.5 (3893.1)	19335.8 (3264.5)	-1	0.62	-0.05 *Trivial*	19437.1 (3590.4)	21559.8 (3437.1)	-11	0.02	-0.61 *Moderate*

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at 0.01 level.

Table 3 – Comparison of normalised asymmetry within non-injured, bilaterally injured and unilaterally injured athlete populations

Measure (Tibia-mounted IMUs)	**Non-injured (N=19)**					**Bilaterally Injured (N=6)**					**Unilaterally Injured (N=8)**				
	Non Dominant - Normalised Mean (SD)	**Dominant - Normalised Mean (SD)**	**%**	**P Value**	**Effect Size**	**Non Dominant - Normalised Mean (SD)**	**Dominant - Normalised Mean (SD)**	**%**	**P Value**	**Effect Size**	**Injured - Normalised Mean (SD)**	**Non Injured - Normalised Mean (SD)**	**%**	**P Value**	**Effect Size**
Total VM	1.58 (0.13)	1.56 (0.14)	2	0.10	0.18 *Trivial*	1.54 (0.18)	1.56 (0.21)	-1	0.56	-0.10 *Trivial*	1.36 (0.24)	1.54 (0.12)	-12	0.03	-0.94 *Moderate*
Medio-Lateral VM	1.78 (0.20)	1.86 (0.23)	-4	0.04	-0.35 *Small*	1.78 (0.22)	1.84 (0.25)	-3	0.45	-0.24 *Small*	1.54 (0.35)	1.74 (0.16)	-12	0.09	-0.74 *Moderate*
Antero-Posterior VM	1.60 (0.15)	1.51 (0.16)	7	**<0.001***	0.60 *Moderate*	1.58 (0.21)	1.57 (0.31)	3	0.71	0.07 *Trivial*	1.35 (0.26)	1.56 (0.18)	-13	0.03	-0.95 *Moderate*
Vertical VM	1.40 (0.17)	1.36 (0.17)	4	**0.002***	0.28 *Small*	1.33 (0.17)	1.35 (0.16)	-1	0.41	-0.12 *Trivial*	1.22 (0.19)	1.35 (0.14)	-10	**0.01***	-0.81 *Moderate*

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

Table 4 – Comparison of normalised asymmetry between non-injured, bilaterally injured and unilaterally injured athlete populations

Measure (Tibia-mounted IMUs)	**Non-injured (N=19) Non Dominant vs. Dominant**		**Bilaterally Injured (N=6) Non Dominant vs. Dominant**		**Unilaterally Injured (N=8) Injured vs. Non Injured**		**Non-injured vs. Bilaterally Injured**		**Non-injured vs. Unilaterally Injured**		**Bilaterally Injured vs. Unilaterally Injured**		**Between All Groups**
	Mean (SD)	**%**	**Mean (SD)**	**%**	**Mean (SD)**	**%**	**P Value**	**Effect Size**	**P Value**	**Effect Size**	**P Value**	**Effect Size**	**ANOVA P Value**
Total VM	1.02 (0.04)	2	0.99 (0.05)	-1	0.88 (0.12)	-12	0.28	0.63 *Moderate*	0.02	1.78 *Large*	0.06	1.06 *Moderate*	**<0.001***
Medio-Lateral VM	0.96 (0.07)	-4	0.97 (0.09)	-3	0.88 (0.18)	-12	0.81	-0.14 *Trivial*	0.23	0.75 *Moderate*	0.23	0.64 *Moderate*	0.16
Antero-Posterior VM	1.07 (0.07)	7	1.03 (0.09)	3	0.87 (0.14)	-13	0.34	0.55 *Small*	**0.01***	2.11 *Very Large*	0.02	1.31 *Large*	**<0.001***
Vertical VM	1.04 (0.04)	4	0.99 (0.04)	-1	0.90 (0.08)	-10	0.04	1.17 *Moderate*	**0.002***	2.36 *Very Large*	0.03	1.22 *Large*	**<0.001***

Notes. IMU; inertial measurement unit, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

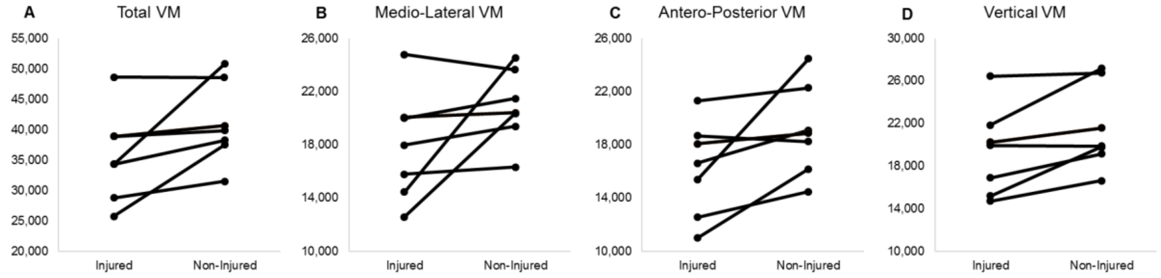


Figure 1 – Non-injured athlete individual vector magnitudes

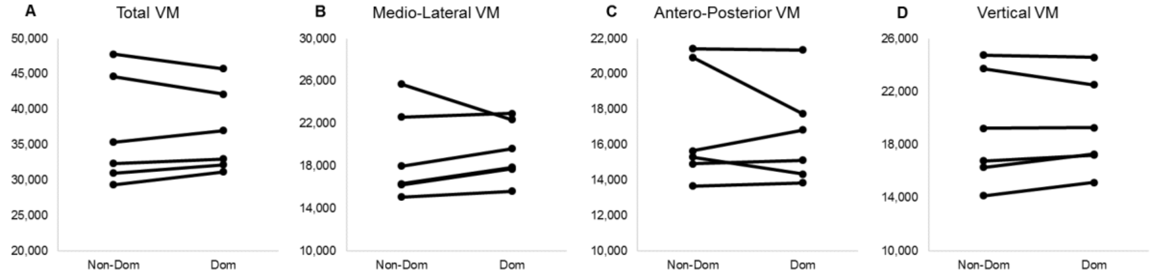


Figure 2 – Bilaterally injured athlete individual vector magnitudes

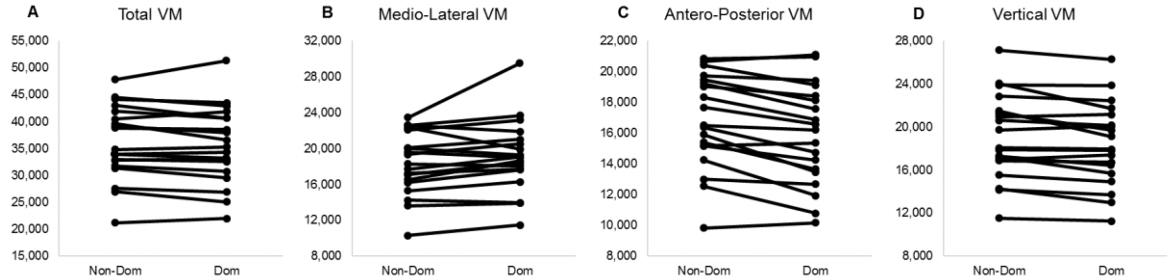
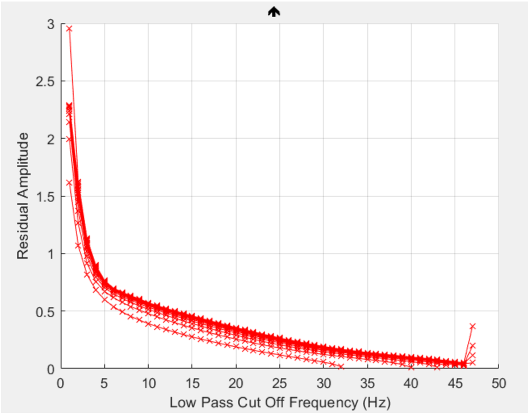
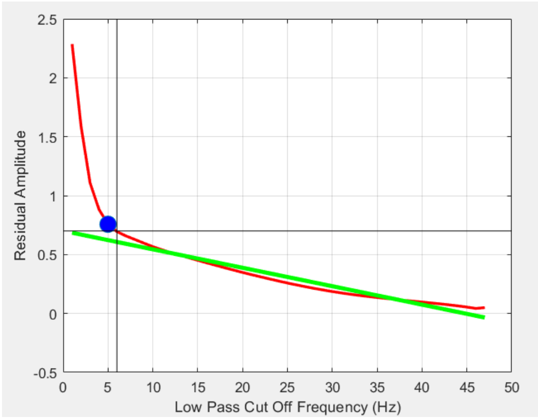
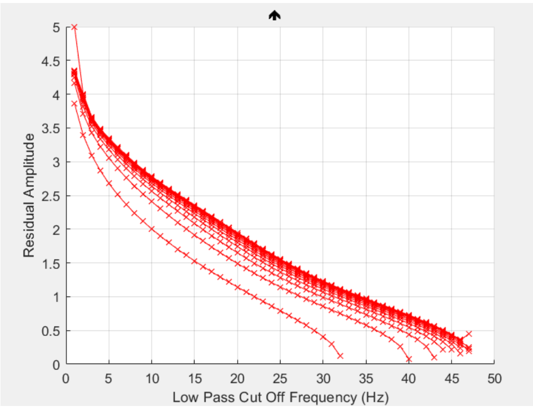
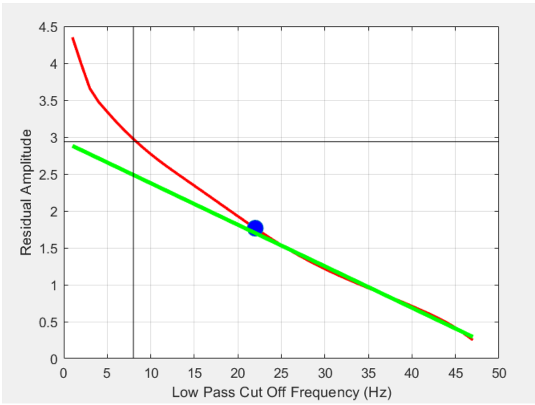
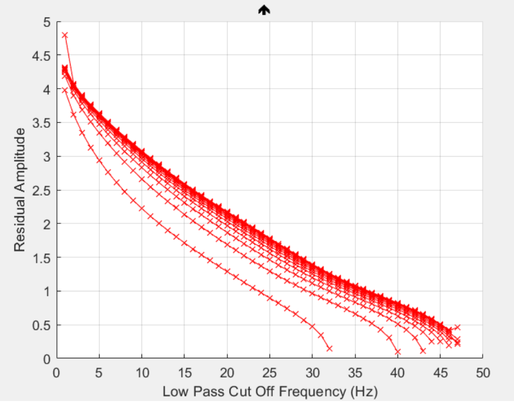


Figure 3 – Unilaterally injured athlete individual vector magnitudes

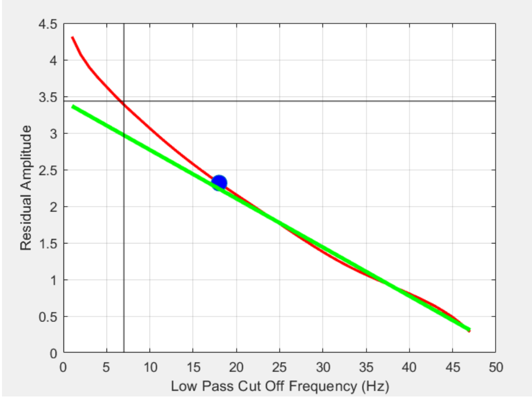
Appendix 8

Residual Analysis of Five Randomly Selected Athletes

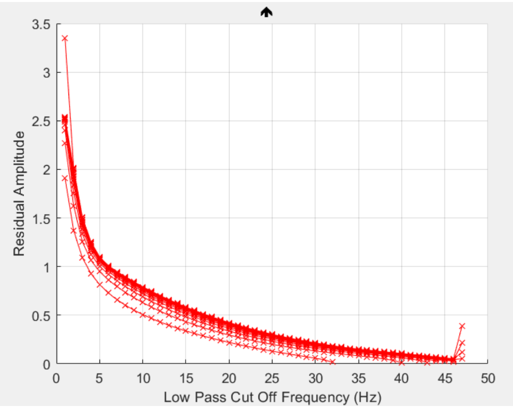
Athlete 1009 Upper Trunk Unit - Poles	Athlete 1009 Upper Trunk Unit - 18 Pole
	
Athlete 1009 Right Tibia Unit - Poles	Athlete 1009 Right Tibia Unit - 20 Pole
	
Athlete 1009 Left Tibia Unit - Poles	Athlete 1009 Left Tibia Unit - 20 Pole



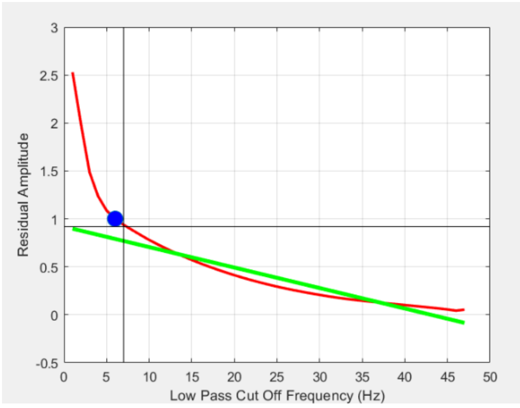
Athlete 2005 Upper Trunk Unit - Poles



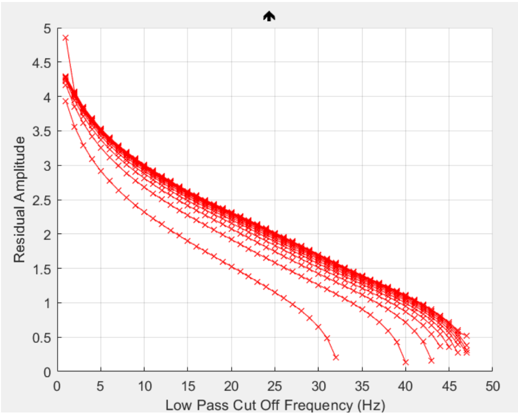
Athlete 2005 Upper Trunk Unit - 18 Pole



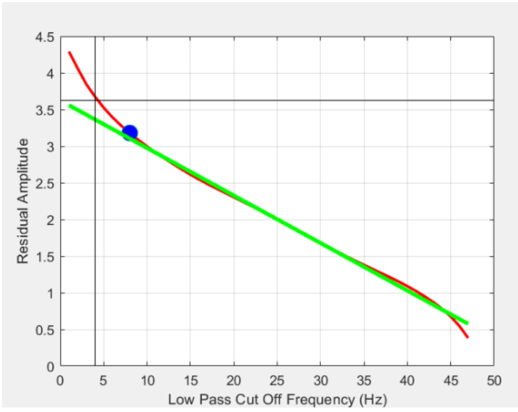
Athlete 2005 Right Tibia - Poles



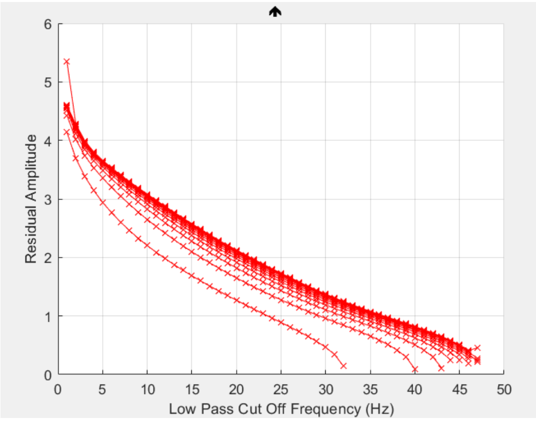
Athlete 2005 Right Tibia - 20 Pole



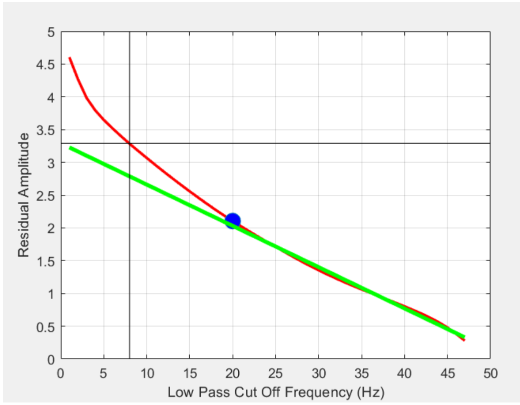
Athlete 2005 Left Tibia - Poles



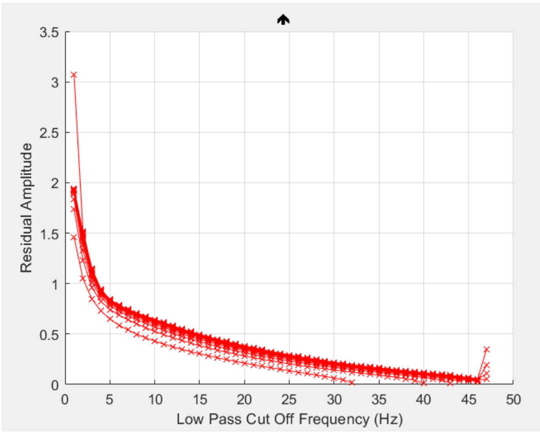
Athlete 2005 Left Tibia - 20 Pole



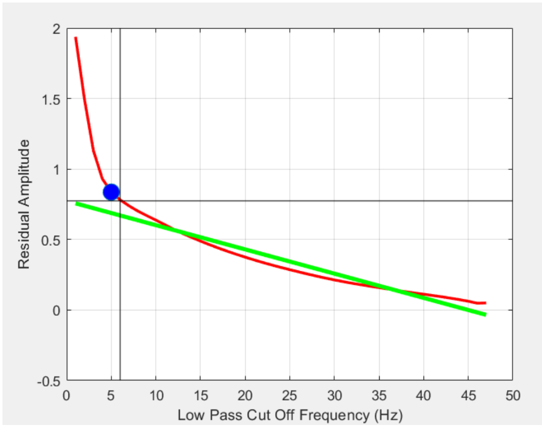
Athlete 2007 Upper Trunk - Poles



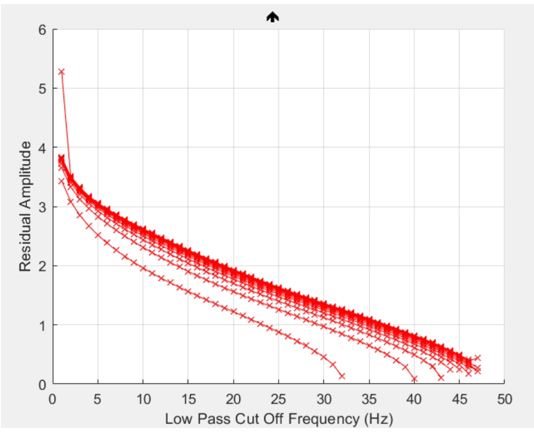
Athlete 2007 Upper Trunk - 18 Pole



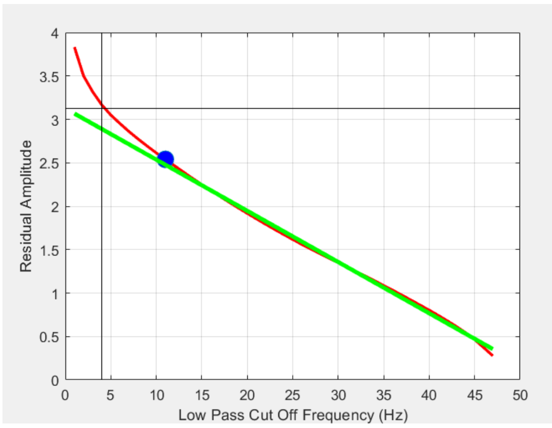
Athlete 2007 Left Tibia - Poles



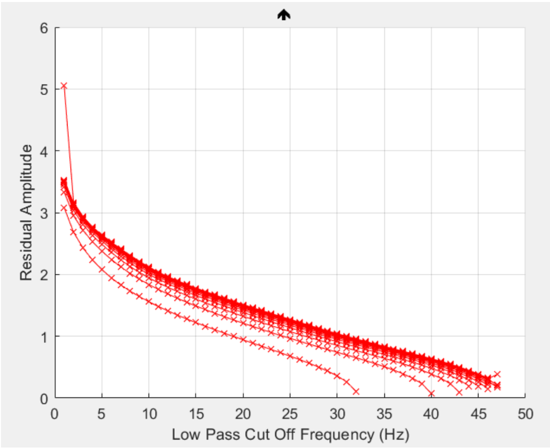
Athlete 2007 Left Tibia - 20 Pole

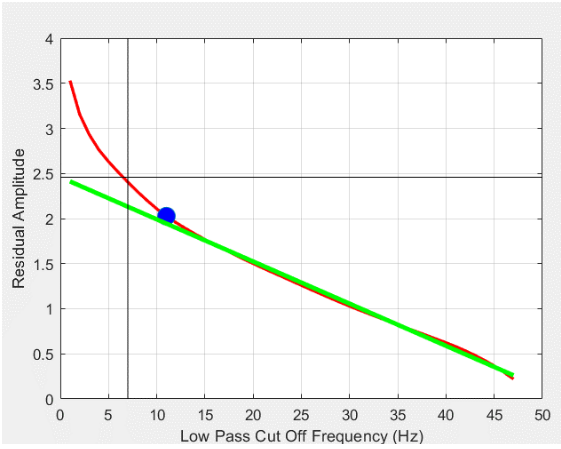


Athlete 2007 Right Tibia - Poles



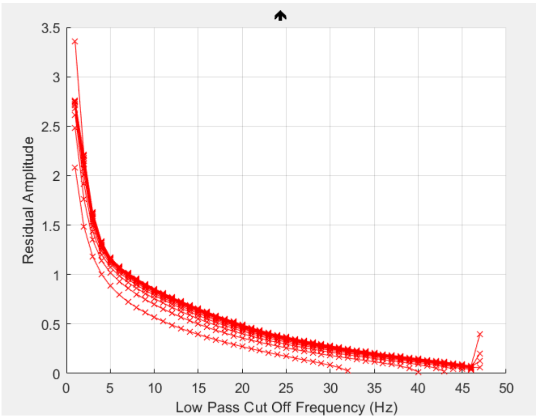
Athlete 2007 Right Tibia - 20 Pole

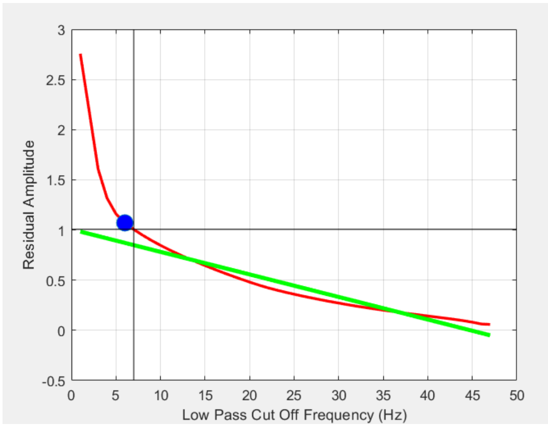




Athlete 2010 Upper Trunk - Poles

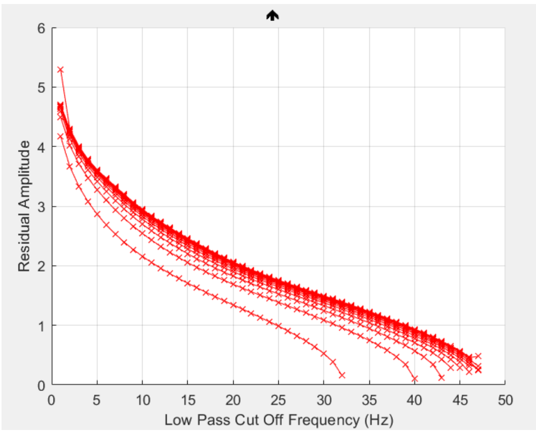
Athlete 2010 Upper Trunk - 18 Pole

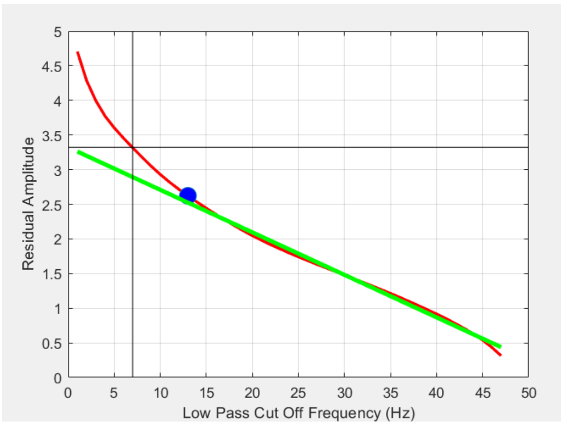




Athlete 2010 Left Tibia - Poles

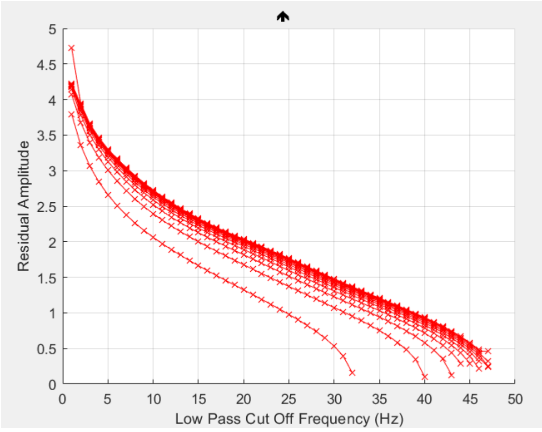
Athlete 2010 Left Tibia - 20 Pole



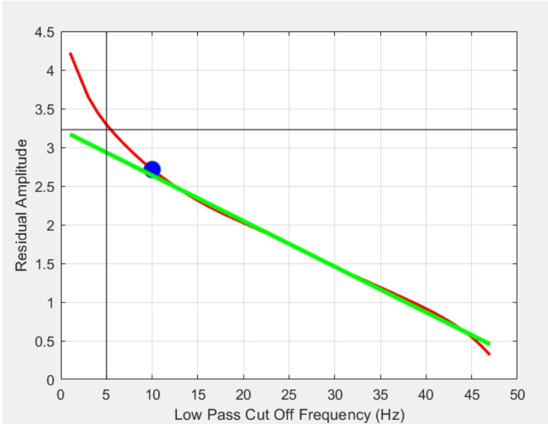


Athlete 2010 Right Tibia - Poles

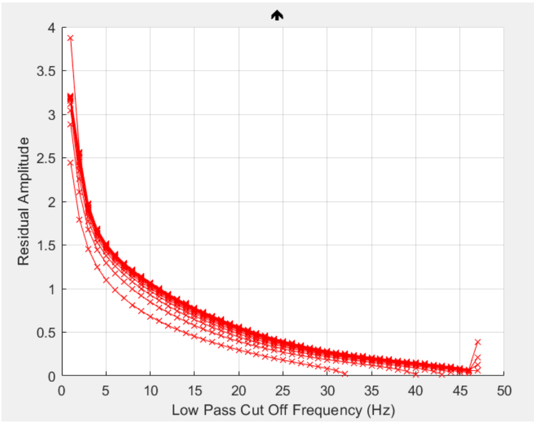
Athlete 2010 Right Tibia - 20 Pole



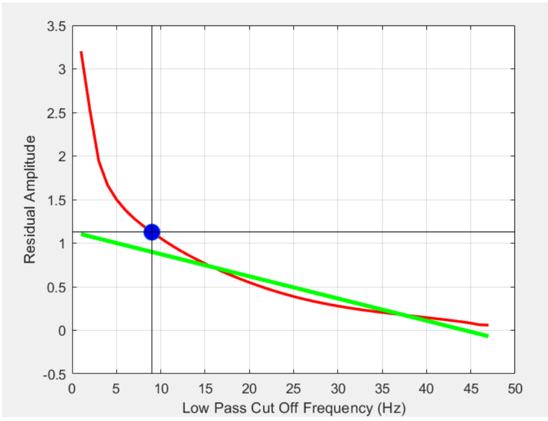
Athlete 3009 Upper Back - Poles



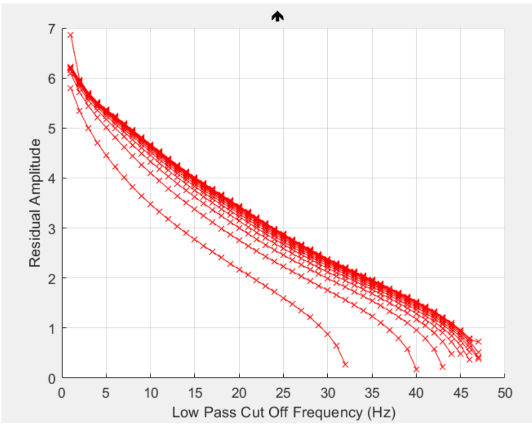
Athlete 3009 Upper Back - 18 Pole



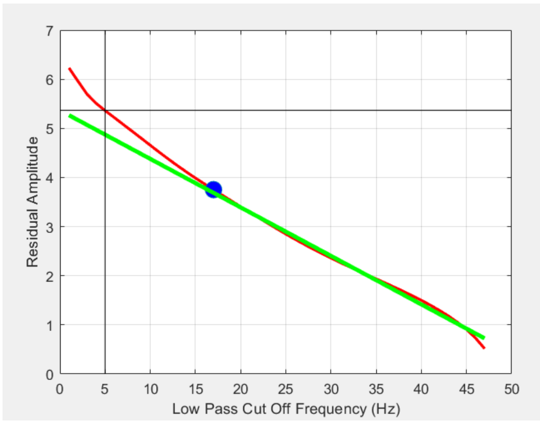
Athlete 3009 Left Tibia - Poles



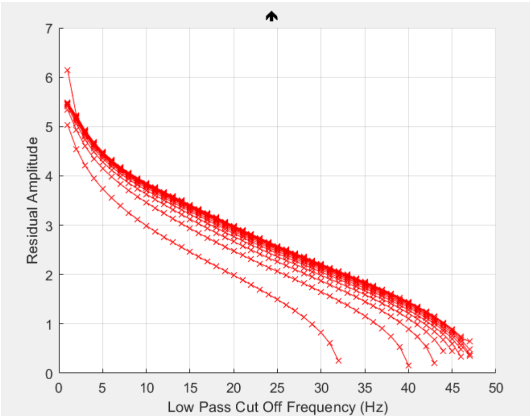
Athlete 3009 Left Tibia - 20 Pole



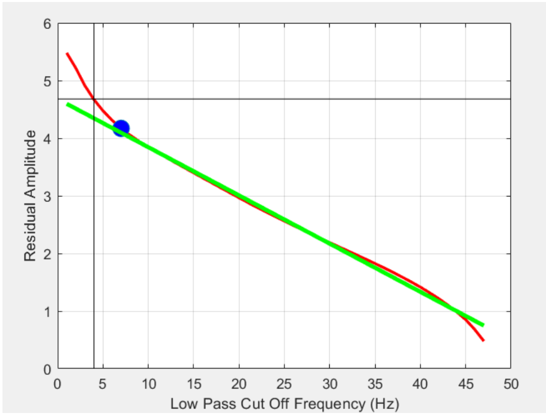
Athlete 3009 Right Tibia - Poles



Athlete 3009 Right Tibia - 20 Pole



Residual Amplitude
Low Pass Cut Off Frequency (Hz)



Residual Amplitude
Low Pass Cut Off Frequency (Hz)

Appendix 9

Bournemouth University

Participant Information Sheet

Project Title: Comparison of Lower Limb Loading Asymmetry Between Badminton Players With and Without Prior Lower Limb Injury

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Invitation

You are being invited to take part in a research project. Before you decide whether to participate it is important for you to understand why the research is being conducted and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask one of the research team if there is anything that is not clear or if you would like more information.

Full title of project:

Comparison of Lower Limb Loading Asymmetry Between Badminton Players With and Without Prior Lower Limb Injury

Name, position and contact details of lead researcher:

Mr Matthew Wylde, Head of Performance Analytics, National Youth Sports Institute /

Postgraduate Research Student, Bournemouth University - matthew_wylde@nysi.org.sg

Name, position and contact details of supervisors:

Dr Andrew Callaway, Senior Lecturer, Sports Performance Analysis, Bournemouth University - acallaway@bournemouth.ac.uk

Dr Jonathan Williams, Deputy Head of Department for Rehabilitation & Sport Science, Bournemouth University - jwilliams@bournemouth.ac.uk

Dr Low Chee Yong, Head of Sport Science, National Youth Sports Institute - low_cheeyong@nysi.org.sg

Background

In youth Badminton, 64% of injuries are soft-tissue sprains and strains with knee injuries being the most common, accounting for 42% of injuries to the lower limbs. These injuries may be avoidable should appropriate loading strategies be adopted. Previous research has demonstrated that a single upper body mounted sensor is unable to accurately measure lower limb loading in youth Badminton players. Studies in other sports have demonstrated that leg worn sensors provide a more direct method for measuring lower limb loading. Further understanding of lower limb loading in Badminton players with and without prior injury, may allow for the design of training programmes to better manage the risk of injury.

Aims

1) Explore the use of leg worn sensors for the measurement of lower limb loading
2) Understand the difference in lower limb loading between Badminton players with and without a prior lower limb injury.

Duration

Data collection will take place during a single training session at the discretion of your coach.

Why were you chosen?

You have been selected as you are a current Badminton player who either has or has not experienced a lower limb injury within the last 5 years.

Do you have to take part?

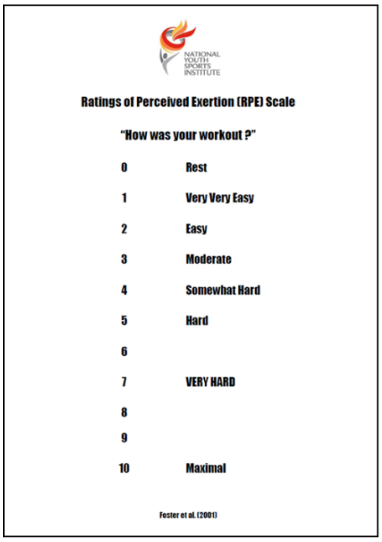
You can decide not to take part at any time during the data collection for any reason. This research investigation is entirely voluntary. If you do decide to take part, you will be given this information sheet to keep (and be asked to sign a participant agreement form) and you can still withdraw during the data collection without repercussions or affecting any benefits, such as team selection, that you may be entitled to in any way. You do not have to give a reason.

What do you have to do?

You will be asked to wear a total of three VXSport athlete tracking units during a single training session. The first unit will be worn between your shoulder blades in a purpose built harness, with the remaining two units worn on the left and right shins. The dimensions of each unit are 74mm x 47mm x 17mm and the weight is 50gm.

Figure 1 – VXSport Unit and Harness

After the training session you will be required to return the VXSport units to be charged and for the session data to be downloaded. At this point you would also be requested to provide Ratings of Perceived Exertion (RPE) for the particular training session. RPE is a scale from 1 to 10 where you can rate the intensity of training (see Figure 2). You will be asked to provide two RPE scores, one for overall load of the session (breathlessness) and one for the tiredness of your legs.



NATIONAL YOUTH SPORTS INSTITUTE

Ratings of Perceived Exertion (RPE) Scale

"How was your workout ?"

0	Rest
1	Very Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	
7	VERY HARD
8	
9	
10	Maximal

Foster et al. (2001)

Figure 2 – RPE Scale and Wellness Monitoring Screenshot

What are the possible disadvantages and risks of taking part?

No changes to you normal training plan are required for this data collection and your coach will be instructed to conduct training as per normal. The positioning of the VXSport units between the shoulder blades and on the shins should have minimal effect on your movement and should not disrupt training.

What are the possible benefits of taking part?

Information from this data collection can be provided to you and/or your coach upon request. This information may enable your coach to design a training programme which better meets your individual needs as a Badminton player.

Will your taking part in this project be kept confidential? / What will happen to the results of the research project?

Your identity and any information will always remain confidential and only be known to the researching team. The research data analysis will be stored by the principal investigator (Matthew Wylde) at the National Youth Sports Institute in Singapore. This data will be kept strictly in accordance with the current Personal Data Protection Act (as enforced by the Personal Data Protection Commission of Singapore). The data will be stored on a secure, password protected laptop owned by the National Youth Sports Institute with file encryption, anti-virus and security software. The data will not be kept longer than is necessary for the purpose of the project and not more than 5 years from the award of the postgraduate degree which this study forms part of.

NOTE: The results of this experiment will potentially form part of future scientific journal publications authored by the researchers. Your identity and participation will not be able to be identified in these. If you are in any way uncomfortable with this arrangement, please notify the researchers before you sign the participant agreement form.

What type of information will be sought and why is the collection of this information relevant for achieving the research project's objectives?

In addition to movement data from the VXSport units and the RPE scores, you will be asked to provide the following information: Age, Height, Weight, Injury History and Number of Years Badminton Playing Experience. For journal publication your identity will not be disclosed.

Contact for further information

If you require any further information, please feel free to contact Mr Matthew Wylde at matthew_wylde@nysi.org.sg.

In case of complaint regarding the data collection please contact Professor Michael Silk (Deputy Dean for Research & Professional Practice, Faculty of Management) via email to researchgovernance@bournemouth.ac.uk.