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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

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A B S T R A C T

Objectives: This study investigates the use of tibia-mounted inertial measurement units (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 to what extent 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 were 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.

1. Introduction

Badminton is characterised by periods of high intensity activity interspersed with short rests (Alcock & Cable, 2009). Badminton has a high prevalence of injury, with an injury incident rate of 11.6 per 1000 h during match-play (Guermont et al., 2021). In Badminton players, lower limb injuries accounted for 54% of all injuries sustained (Guermont et al., 2021), highlighting lower limb injuries as an area of concern.

In addition to lower limb injuries, structural asymmetries between the lower limbs have been reported in Badminton players. Greater width and thickness of the patellar and Achilles tendon have been identified in the dominant leg in professional Badminton players (Bravo-Sanchez et al., 2019). Furthermore, during step forward lunge and jump lunge tasks, it was found that the dominant leg produced greater force (Nadzalan et al., 2017).

Lower limb asymmetry has been associated with poorer jump performance, change of direction speed and agility and has been linked to injury risk (Hoffman et al., 2007; Bell et al., 2014; Steidl-

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Müller et al., 2018; Madruga-Parera et al., 2020; Helm et al., 2021). The limb symmetry index is a frequently used metric in sports medicine (Abrams et al., 2014; Engelen-van Melick et al., 2013) and is a commonly used rehabilitation target following knee ligament injuries (Almangoush & Herrington, 2014). To that end, the value of <10% limb asymmetry is a common return to sport criterion (Abrams et al., 2014; Schmitt et al., 2012) for both strength (Brown et al., 2020) and functional performance testing such as hopping distance (Almangoush & 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 single leg counter movement jump for distance test, which has been used to assess asymmetry in racket sport athletes (Madruga-Parera et al., 2020), is not an exact representation of the functional requirements of the 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 and return to play.

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). Common practice for the measurement of training magnitudes is to use upper trunk-mounted IMUs. This device location has been found to be poor in estimating vertical acceleration of the centre of gravity or vertical ground reaction forces during running (Edwards et al., 2018), which would be important for determining asymmetry. 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.

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 assessment of movement asymmetries and as part of return from injury monitoring, 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 to what extent Badminton players exhibit movement asymmetry during simulated match-play and, (3) explore asymmetry indexes of Badminton players with no, uni-, bi-lateral injury history.

2. Methods

2.1. Experimental design

This study utilised a cross sectional, observational study design. All data were collected during 90 min of simulated match-play within a high-performance training centre during a normal 3-h badminton training session. Each participant wore three VXSport (Visuallex Sport International, Lower Hutt, New Zealand) log units (dimensions: 74 mm × 47 mm × 17 mm, weight: 50 g). 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 Fig. 1). The study was approved by the Singapore Sport Institute Institutional Review Board.

2.2. Participants

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). Informed assent was obtained from all participants and informed consent was obtained from each participant's parent/legal guardian. The sample size was determined using data from a study of asymmetry in youth Tennis players (Madruga-Parera et al., 2020), 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

Fig. 1. IMU secured on the mid-tibia using adhesive tape.

athletes with an injury to one lower limb and the *bilaterally injured group* 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 3 consecutive training sessions.

2.3. Data collection

Prior to the commencement of the data collection the athletes took part in a standardised team warm-up as prescribed by the coach. The data collection duration lasted for 90 min 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 from the three IMUs were recorded at 100 Hz. Post data collection, each athlete was asked to complete a questionnaire reporting any lower limb injuries sustained during the previous 2 years.

2.4. Data analysis

Using the acceleration data, filtering frequency was determined by residual analysis (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 7 Hz for the scapulae units, and 6 Hz for the tibia units, and mean centred in Matlab (MathWorks, Natick, MA, USA).

Training magnitudes were reported as arbitrary units (AU) and 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)). 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

$$Vertical\ VM = \sqrt{\frac{(az_1 - az_{-1})^2}{100}}$$

$$Antero-Posterior\ VM = \sqrt{\frac{(ay_1 - ay_{-1})^2}{100}}$$

$$Medio-Lateral\ VM = \sqrt{\frac{(ax_1 - ax_{-1})^2}{100}}$$

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 (Schiltz et al., 2009).

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

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

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

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

2.5. Statistics

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”.

3. Results

All 33 athletes completed 90 min 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

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 (AU)	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 (AU)	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 (AU)	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 (AU)	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, AU; arbitrary units, 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 (AU)	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 (AU)	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 (AU)	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 (AU)	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, AU; arbitrary units, SD; standard deviation, N; number of athletes included. * denotes statistical significance at 0.01 level.

the antero-posterior axis and vertical axis (see Fig. 2). 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 Fig. 3). By contrast, 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 Fig. 4).

4. 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 to what extent 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 reducing the validity of the training load measures (Derrick et al., 1998; Glassbrook et al., 2020). 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 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 (Abrams et al., 2014; Schmitt et al., 2012), 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 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. In this study all participants were right-handed

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 (AU)	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 (AU)	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 (AU)	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 (AU)	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, AU; arbitrary units, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

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., 2010), 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 the bilaterally injured group, with significantly lower asymmetry observed for vertical VM in the bilaterally injured group compared to the non-injured group. Given that landings 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 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 for 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 (Abrams et al., 2014; Schmitt et al., 2012), 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 impacts vertical jump performance and change of direction speed in youth racket sport players (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.

The results of this study demonstrate that, compared to non-injured and bilaterally injured players, those with unilateral lower limb injury had asymmetries of between 11 and 16%. This finding is novel in 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 (Sharafoddin-Shirazi et al., 2020). It is possible these alterations serve as a protective strategy to reduce the load on the injured limb, therefore minimising the provocation of pain. This is due to a well-documented response to pain where the body seeks to minimise

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 (AU)	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 (AU)	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 (AU)	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 (AU)	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, AU; arbitrary units, SD; standard deviation, N; number of athletes included. * denotes statistical significance at ≤0.01 level.

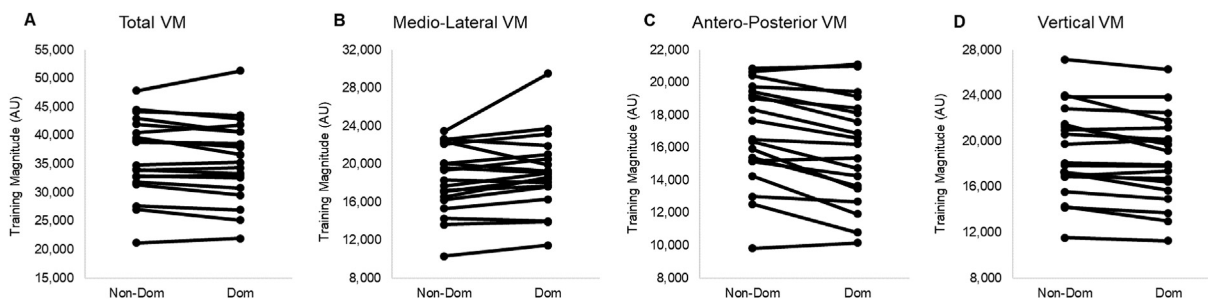

Fig. 2. Individual total and axis-specific training magnitudes for the non-injured athletes (Arbitrary Units; AU).

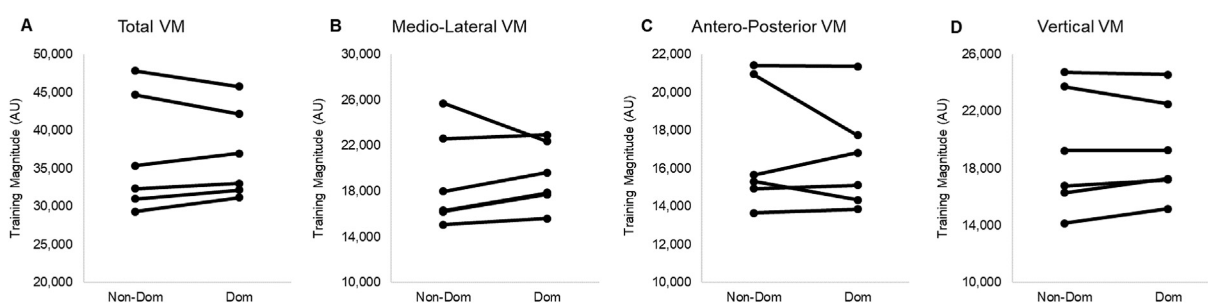

Fig. 3. Individual total and axis-specific training magnitudes for the bilaterally injured athletes (Arbitrary Units; AU).

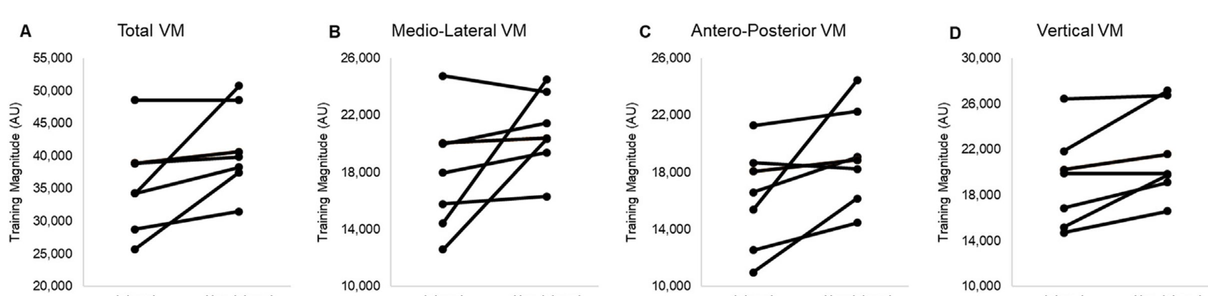

Fig. 4. Individual total and axis-specific training magnitudes for the unilaterally injured athletes (Arbitrary Units; AU).

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.

Conversely, these alterations may represent sub-optimal recovery from the injury where lingering deficits in unilateral limb performance remain. 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 et al., 2014). In this case, targeting this sub-optimal function may prove beneficial to close the symmetry gap.

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 immediately 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.

4.1. Practical applications

The quick and simple method employed in this study was able to determine that players with a previous unilateral injury may harbour lingering lower limb asymmetry, evident during simulated Badminton match-play. This suggests the current method of measuring magnitude of use of lower limbs through tibia-mounted IMUs is sensitive enough to detect these asymmetries. The cause of such asymmetries is not clear, but as pain is no longer present, they may suggest lingering deficits in sport specific function. The use of tibia-mounted IMUs could be employed to determine the recovery from injury and used as a specific rehabilitation target. 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.

4.2. Limitations

A limitation of this study is 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 this study the IMUs were attached to the mid-tibia using adhesive tape, which was feasible for the purpose of the study but not for a longitudinal study as daily monitoring would be difficult. Other brands of IMU, for example IMeasureU Blue Trident (Vicon Motion Systems Ltd, Oxford, UK) and Xsens Dot (Xsens Technologies, Enschede, Netherlands) are specifically designed to be worn at the lower limbs and are smaller and lighter than the VX Sport units. The use of these smaller units would facilitate a smoother data collection process and allow for longitudinal studies of lower limb loading in Badminton and other court-based sports to be conducted with ease. 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. A longitudinal study would allow for changes in lower limb asymmetry and training magnitude 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.

5. Conclusion

This study has demonstrated that training magnitudes from tibia-mounted IMUs are able to differentiate between adolescent Badminton players with and without unilateral and bilateral lower limb injury history, which could not be achieved using a single upper trunk-mounted IMU. Lower limb asymmetries of >10% were recorded in the groups with unilateral injury history which were not present in the bilaterally injured and non-injured groups. This does draw into question the current processes of assessment within the sample population, as players with unilateral injury history but no current lower limb injuries still broke the 10% threshold for clinical asymmetry. 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 and have the potential to be used for both regular training monitoring and as part of return to training protocols.

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Ethical approval

This 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.

Declaration of competing interest

None declared.

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