

**An Insight into the Acceptable Use &
Assessment of Lower-limb Running Prostheses
in Disability Sport**

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DEDICATION

This thesis is dedicated to the memory of Jeff Dyer (1949-2012).

A great father, whose mental and physical endurance were
without equal.

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ABSTRACT

Sports technology can be any product or system used to facilitate, train or influence an athlete's performance. The role of prostheses used for disability sport was initially to help facilitate exercise and then ultimately, competition. In able-bodied sport, controversy has occasionally been caused through the adoption or introduction of sports technology. However, scant attention has been paid to sport with a disability with respect to such concerns. This research project provides a novel contribution to knowledge by investigating the use of lower-limb running prostheses in competition by trans-tibial amputees.

A novel study using a mixed method approach has investigated the nature, use and assessment of lower-limb running prostheses. It has proposed that the unchecked introduction of such technology has affected the sport negatively. From this, the study conducted a stakeholder assessment of the sport and provided a proposed series of guidelines for lower-limb prostheses technology inclusion. Finally, the recommendation was made that a proactive approach to such technologies' inclusion in the future should be implemented.

These guidelines were further developed by assessing symmetrical and non-symmetrical lower-limb function and proposed that single and double lower-limb amputees should be separated in competition in the future. To this end, it was proposed that lower-limb symmetry, stiffness and energy return were important means of monitoring prosthesis performance. Ultimately, a dynamic technique which assesses these qualities was proposed as an assessment strategy for further development in the future.

CONTRIBUTION TO KNOWLEDGE

The novelty or 'contribution to knowledge' of this project is that no study to date has investigated the role, perception and impact of running lower-limb prosthesis used specifically in a mixed amputee classification in disability sport. In addition, having investigated such aspects, this study reveals several issues with respect to their use so provides proposed guidelines for the evaluation and assessment of such technology and a proposed technique for doing so.

The project uses a novel mixed methods research approach to provide a pragmatic insight into the research objectives and provides direction for future research to build on this study's recommendations.

NOMENCLATURE

AS – *Amputee Sprinting*

CV – *Coefficient of Variation*

DETRIS – *Dynamic Elastic Response to Timed Impulse Synchronisation*

ESR – *Energy Storage & Return Prostheses*

ESRF – *Energy Storage & Return Footwear*

FDE – *Fixed at Distal End*

IAAF – *International Association of Athletics Federations*

IOC – *International Olympic Committee*

IP – *Able-bodied Inception Period*

IPC – *International Paralympic Committee*

JOST – *Jog On the Spot Test*

LLP – *Lower-limb Prostheses*

LLRP – *Lower-limb Running Prostheses*

LA – *Lower-limb to Limb Asymmetry*

LS – *Lower-limb to Limb Symmetry*

MMR – *Mixed Method Research*

MP – *Able-bodied Modern Period*

PII – *Performance Improvement Index*

RA – *Random Asymmetry*

SDE – *Slide of Distal End*

SI – *Symmetry Index*

T43 – *Double Below-knee Amputee*

T44 – *Single Below-knee Amputee*

WADA – *World Anti-doping Agency*

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

Lower-limb prostheses (LLP's) have provided the means for an amputee with a lower-limb amputation to participate in competitive sport (Lewis et al. 1996). However, sport can extend from participation into an arena of elite competition. An example of competitive amputee running is shown in figure 1.



Figure 1: Lower-limb Amputee Competition (www.bbc.co.uk)

To attain the best possible performance, effort must be made to optimise the various components that can contribute to an athletes' success such as their training, nutrition or equipment. Typically, a sports technology is regulated via a sport's governing body to ensure that the role and regulation of such technology is known. Despite this, the type of technology employed by athletes in a sport can affect the performance outcome. Whether this is deemed right or fair is typically determined by the constitutive rules of a

sport's governing body. Such discussion of technology inclusion is often attempted to be resolved in academic areas of study such as *sports philosophy* (Lavin 2003) or *sports engineering* (James 2010). However, applying these perspectives independently of each other can have limitations. Sports ethics can provide a wide range of viewpoints but only moralise 'on paper' (Kretchmar 1984). Likewise, sports engineering can provide empirical evidence to address a stated controversial issue, yet does not consider the ramifications of its findings in a sport (Bruggemann et al. 2008). As a result, utilising the strengths of both methods may well be a better solution.

LLP's used for running at competitions such as the Paralympic Games has typically been described as technology to *facilitate* a sport (Burkett 2011). An example of a typical LLP is shown in figure 2.



Figure 2. Running Lower-limb Prostheses (www.dorset-ortho.com)

Thus, LLP's are integral to the performance of an athlete (Nolan 2008). Without them, the athlete would be unable to run. Historically though, little

attention was paid to the regulation of such technology until 2008 whereby South African Oscar Pistorius attempted to qualify for the Olympic Games using LLP's. Debate raged over whether his LLP's were judged to be performance enhancing. The outcome of the ensuing investigation into Pistorius raised conflicting opinions on how prostheses in sport should be regarded. Ironically accusations into prosthesis technology were made by Pistorius and later American Jerome Singleton in post race BBC interviews at the London 2012 Paralympic Games. As such, further investigation into the role and use of LLP technology in disability sport would seem of timely value. If concerns into the use of LLP technology do exist, assessment and regulation strategies should be implemented to maintain the 'level playing field' of the running events. This research project will provide new knowledge by attempting to investigate and define the role of LLP technology in elite disability sport. It will examine whether any potential unfairness actually exists, and if so, to investigate strategies to improve these in the future.

1.2 OBJECTIVES

The objectives of this study were:

- To investigate the impact of any prostheses technological change that has occurred in the sport and to ascertain whether any regulation on their acceptability would be of value in the future.
- To investigate current perceptions of lower-limb running prosthesis used in competitive disability sport.
- To propose guidelines for lower-limb prosthesis technology inclusion when used in competitive running with a lower-limb amputation.
- To investigate the assessment of lower-limb running prosthesis and to recommend appropriate testing strategies.

1.3 SCOPE OF RESEARCH

This research investigated the use of lower-limb prosthetics in disability sport running. The context was limited to the male shorter running distances used in the Paralympic Games. These are traditionally the 100m and 200m. Both short running distances and male competitors are the only aspects which have seen consistent participation during modern Paralympic Games history. The project focused on athletes who have below-knee amputations as these also have the highest levels of continuous participation at the Paralympics and in greater numbers. The project does not focus on the use of such technology for above-knee amputees or for the use of such technology when used in able-bodied sport - even if some of the study's findings may be applicable to that context.

1.4 BENEFICIARIES

The project primarily provides guidelines and empirical evidence that are of value to the governance of elite sport with a disability. Such findings contribute to any discussion for any rule proposal amendments the governing body may wish to suggest in the future. Indirectly, the research findings may also provide strands of research that prosthesis manufacturers may pursue to assist in the optimisation of clinical prosthesis designs in the future.

1.5 STRUCTURE OF THESIS

The thesis consists of 11 chapters. The synopsis for these is shown below in table 1.

Table 1. Thesis Content

Chapter	Synopsis
1	Introduces the project, its background and provides the rationale for the research area.
2	Covers a literature review of amputee running, prosthesis technology and how it is regulated in disability sport. It was proposed that this area has seen little attention and is worthy of further study.
3	Reviews the controversy surrounding the use of technology in sport and what methods have been used endorse or reject them. In addition, the current legislation for the use of prosthesis in disability sport was reviewed and its limitations investigated. It is proposed that issues surrounding an unacceptable use of prostheses technology <i>may</i> exist but that this research area was a gap in current knowledge. These issues were therefore investigated in chapters 5 and 6.
4	Details the general research methodology of this research project and the rationale for doing so. A mixed-method research approach was

	defined and selected.
5	Assesses the impact of a known technological change in prosthetics technology and determines its impact in disability sport. This chapter demonstrated the impact when technology is left unregulated within short distance amputee running competition. It is proposed that the adoption of LLP's may have created participation issues in the sport. Accepting such technology is currently the norm, the perceptions of this current technology were investigated in chapter 6.
6	This chapter performed a stakeholder assessment to develop guidelines for the acceptable inclusion of prosthetics technology in disability sport. This determines the core philosophy when designing any assessment strategies of running prosthesis in the future. Stride length was referred to as an issue and this was investigated in chapter 7. The proposed guidelines also raised question marks over the differences between uni-lateral and bi-lateral lower-limb amputees. This aspect was investigated in chapter 8.
7	This chapter investigated the stride characteristics of athletes with lower-limb amputations competing in the 100m in disability sport. It confirms the qualitative findings of chapter 6 that inter-limb symmetry should be monitored.
8	This chapter investigated whether bi-lateral and uni-lateral amputees have functional differences between them as a result of changes in energy return technology. It used a jog hop test technique to create cyclic lower-limb to limb ground impacts. This study was important as it addressed chapter 6's finding in that whether single and double amputees should continue to race together in a combined classification. This informed the design of a proposed assessment strategy in chapter 10.
9	This assessed regulating prosthetics technology using 2 different loading methods when in isolation from its user. This extended the finding in chapter 6 in that prostheses are 'equipment' but ultimately conceded that such technology cannot be assessed in isolation from its user. This admission also contributed to the proposed assessment

	strategy in chapter 10.
10	This assessed the limitations of regulating prosthetics technology by proposing a jump test method. The technique was demonstrated to be suitable but warranted further development in the future.
11	This discussed and concluded all chapters and gave recommendations for future actions leading from this projects overall research problem.

A graphical representation of the thesis chapters and their linkages is shown in figure 3.

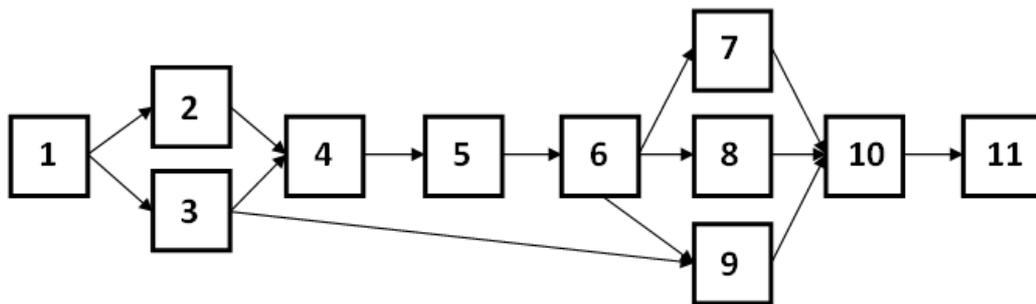


Figure 3. Thesis Chapter Linkages

1.6 ETHICAL APPROVAL

Several experiments within this thesis required ethical approval as they required human participation. This approval process was submitted to the Research Ethics Committee located within the School of Design, Engineering & Computing School at Bournemouth University. The Delphi study in Chapter 6, the jog/hop tests in Chapter 8, the run tests in Chapter 9 and the drop jumps tests in Chapter 10 all required and obtained ethical approval.

1.7 RESEARCH PUBLICATIONS

Several elements of the research in this thesis have been published in internationally recognised journals and conferences. This process has been undertaken as a means of peer review throughout the course of this research project. The journal papers are contained within Appendices F.

1.7.1 Journal Papers

Dyer, B. T. J., Sewell, P., Noroozi, S. 2013. How should we assess the mechanical properties of lower-limb prosthesis technology used in elite sport?: an initial investigation. *Journal of Biomedical Sciences & Engineering*. 6, 2, 116-123.

Noroozi, S., Sewell, P., Rahman, A., Vinney, J., Ong Zi Chao., & Dyer, B., 2012. Performance enhancement of bi-lateral lower-limb amputees in the latter phases of running events: an initial investigation. *Proceedings of the Institution of Mechanical Engineers Part P: Journal of Sports Engineering and Technology*. doi:10.1177/1754337112451959

Noroozi, S., Sewell, P., Vinney, J., Dyer, B. T. J., Rahman, A. G. A., & Zhi Chao, O., 2012. Modal analysis of composite prosthetic energy-storing-and-returning feet: an initial investigation. *Proceedings of the Institution of Mechanical Engineers Part P: Journal of Sports Engineering and Technology*. doi:10.1177/1754337112439274

Dyer, B. T. J., Sewell, P., Noroozi, S., Broomfield, S., & Callaway, A., 2012. Sprint prostheses used at the Paralympics: a proposal for an assessment method to maintain fairness. *Prosthetics and Orthotics International*, 36, 3, 306-311.

Dyer, B., Noroozi, S., Sewell, P., & Redwood, S., 2011. The fair use of lower-limb running prostheses: a delphi study. *Adapted Physical Activity Quarterly*, 28, 16-26.

Dyer, B., Noroozi, S., Sewell, P., & Redwood, S., 2010. The design of lower-limb sports prostheses: fair inclusion in disability sport. *Disability and Society*, 25, 593-602. doi:10.1080/09687599.2010.489309

1.7.2 Conference Publications

Dyer, B. T. J., 2013. 100M Sprinting with an Amputation: Some Technological Considerations for Success. *In: UK High Performance Conference for Paralympic Sport Science and Sport Medicine*. UK.

Dyer, B. T. J., 2013. Scribble, Sketch, Carve, Wrench and Spin': A Case Study of a Paralympian's Cycling Prostheses Design, *In: UK High Performance Conference for Paralympic Sport Science and Sport Medicine*. UK

Dyer, B. T. J., 2012. Sports Prostheses, Performance & Ethical Impact. *In: Nordic NOIF Conference 2012*. Oslo. [Invited Speaker]

Dyer, B. T. J., 2012. An investigation into the development, perception and assessment of lower-limb running prosthetics technology in Paralympic sport. *In: ICSEMIS 2012*. Glasgow. [Invited Speaker]

Dyer, B. T. J., 2011. Design & technology within elite sport: philosophy, engineering & prosthesis. *In: 2nd Sporting Prosthetics Conference 2011*. Hampden National Stadium, Glasgow, Scotland. Retrieved from <http://www.strath.ac.uk/prosthetics/research/speeadsportingprosthetics/sportingprostheticsconference111111/> [Invited Speaker]

Dyer, B. T. J., 2010. The evolution of lower-limb prostheses for running in elite sport. *In: World Congress of Science in Athletics*. Barcelona, Spain. Retrieved from <http://www.cidida.org/index.asp?s=&id=> [Invited Speaker]

Dyer, B. T. J., Noroozi, S., Sewell, P., & Redwood, S., 2010. An argument for assessing lower-limb sprinting prostheses technology. *In: 13th ISPO World Congress*. Leipzig, Germany. Retrieved from http://www.ot-forum.de/trade_shows_congresses/orthopaedics_reha_technology/ispo_world_congress [Invited Speaker]

Van de Vliet, P., & Dyer, B. T. J., 2010. Technology & sports: the future of paralympic sports. *In: 13th ISPO World Congress*. Leipzig, Germany. Retrieved from http://www.ot-forum.de/trade_shows_congresses/orthopaedics_reha_technology/ispo_world_congress___or_2010 [Invited Speaker]

Dyer, B. T. J., 2009. The fair regulation of lower-limb prostheses technology in paralympic running. *In: Paralympics GB National Conference*. Loughborough University.

1.7.3 Selected Public Engagement

2013: 'The fastest men on no legs': The Skinners School, Royal Tunbridge Wells, Kent, 8/7/13.

2013: 'Lights, camera's & some action': Cafe Scientifique – European College of Chiropractic, Boscombe, Dorset, 10/6/13.

2012: 'Prosthesis & sports technology': Cafe Scientifique - Cafe Boscanova, Boscombe, Dorset, 6/11/12.

2012: Interview with Huw Edwards on BBC News - Controversy of prosthetic limb length at the 2012 Paralympic Games. 5pm, 3/9/12.

2012: Interview on BBC Radio Solent: Controversy surrounding sports technology 1pm, 29/8/12.

2012: Interview on TalkSPORT radio - Sport & Technology. 22/3/12.

2011: Pilgrim Bandits amputee trekking training weekend. Snowdonia, Wales.

1.7.4 Prizes

2013: British Science Festival – Isambard Kingdom Brunel Award Lecture

2012: Times Higher Education Awards - Shortlisted for 'Outstanding Contribution to Innovation & Technology'.

2011: Vice Chancellors Awards – ‘Research & Enterprise Project of the Year’ (with Dr Philip Sewell & Prof. Siamak Noroozi).

2010: Times Higher Education Awards - Shortlisted for 'Outstanding Engineering Research Team of the Year' (with Dr Philip Sewell & Prof. Siamak Noroozi).

2009: Paralympics GB Conference - Runner Up , Research Prize.

2009, 2010 & 2012: Best Postgraduate Student Research Poster, Bournemouth University.

1.8 BACKGROUND

This section provides a background and context to the research problem. It also provides an overview of amputees, disability sport and its governance.

1.8.1 Amputation & Amputees

Amputation is whereby one or more of the upper or lower limbs are removed due to trauma, congenital defects and blood flow issues (Powelson & Yang 2012) that cannot be remedied using medical science of that time (Couch et al. 1977). It is also undertaken to preserve maximum independence of action for as long as possible (Geertzen et al. 2001). Prior to discoveries like antibiotics, amputation was the only medical procedure available to treat infections of the limbs (Coakley 2002). Prior to the widespread use of anaesthesia, such surgery carried a high risk of death due to haemorrhage or infection (Thurston 2007). One of the earliest examples of amputation is of a large toe amputation having been discovered on a 5000 year old Egyptian mummy (Thurston 2007).

The goals of modern surgery are to remove the damaged limb segment(s) and then to fashion a residual limb that interfaces effectively with a prosthesis (Michael & Bowker 1994). Rehabilitation from amputation is affected by the severity and magnitude of limb removal (Couch et al. 1977). The ultimate goal for the patient is to resume a full and active lifestyle (Gutfleisch 2003).

In terms of definition, leg or lower-limb amputation can be summarised as *below-knee* and *above-knee* (Couch et al. 1977). Alternatively, this has also been summarised as *trans-femoral* (above-knee) or *trans-tibial* (below-knee) (Powelson & Yang 2012). In general, the greater the level of amputation, the

greater the functional loss for the amputee (Michael & Bowker 2004). Preservation of the knee joint in particular is, desirable as this maintains joint articulation therefore making use of a prosthesis easier (Couch et al. 1977).

Post surgery treatment surrounding amputation is an ongoing process which covers issues such as fluctuating residual limb volume and prosthetic fit (Michael & Bowker 2004). The quality of such fit between prosthesis and athlete is fundamental to the overall performance of the athlete (Burkett 2011). In addition, managing soft tissue injuries due to the competitive use of assistive devices such as prosthesis is also a concern (Nyland et al. 2000).

1.8.2 History of Disability Sport

The Olympic Games is the largest sporting event in the world (Kioumourtzoglou & Politis 2002). The largest equivalent for athletes with a disability is the *Paralympic Games* (Kioumourtzoglou & Politis 2002). The 'Paralympics' cover six core disability groups – athletes with cerebral palsy, athletes with intellectual disabilities, athletes with visual impairment, athletes with spinal cord injuries, Les Autres (French for 'the others') and athletes with an amputation (Gold & Gold 2007). Whilst other competitions for those with a disability exist, it is the Paralympics which form the pinnacle of athletic excellence.

Whilst participation for those with a disability can be traced back to events such as the first International Silent Games in 1924 for athletes suffering for hearing impairments (Gold & Gold 2007), the birth of what became the Paralympic Games did not take place until after the Second World War. The history of the Paralympics is credited to the work of Dr Ludwig Guttman, a neurosurgeon who founded the spinal cord injuries centre located at Stoke Mandeville in Buckinghamshire, England in 1944 (Brittain 2012). Following the Second World War, the British Government requested that Guttman

establish a spinal cord injuries centre typically catering for ex-servicemen (Gold & Gold 2007). Guttman made competitive sport an integral part of the rehabilitation process for those with spinal cord injuries (Legg & Steadward 2011). In 1948, two teams took part in an archery contest on the front lawns of Stoke Mandeville Hospital (Kioumourtzoglou & Politis 2002) to coincide with the opening ceremony of that year's Olympic Games held in London (Gold & Gold 2007). In 1949, Guttman saw the potential for such competitions to become an equivalent of the Olympic Games and in 1952, a smaller competition took place across several sports disciplines (Kioumourtzoglou & Politis 2002). This saw international participation (Vanlandewijck & Chappel 1996) involving competitors from the Netherlands (Bressan 2008; Legg & Steadward 2011). Pope John Paul XXIII later declared Guttman the 'Coubertin of the paralysed' (Legg & Steadward 2011) suggesting parallels to the longer established Olympic Games that Guttman had attempted to replicate. By 1960, the first official summer Paralympic Games took place in Rome (Vanlandewijck & Chappel 1996) and saw 400 athletes from 23 countries competing (Kioumourtzoglou & Politis 2002). Athletics was included in the full Paralympic programme for the first time in 1960 (Gold & Gold 2007) and in 1976, the scope of the Paralympics was widened to accept other disabilities (Curran 2012) including amputees (Webster 2001).

In 1988 the Paralympics and Olympics were held together in the same year using the same hosting city and venues (Brittain 2012). In 2001 the IOC and the IPC signed an agreement which established closer ties between the two organisations. This strengthened the finances of the International Paralympic Committee (IPC) but the International Olympic Committee (IOC) also insisted that the Paralympics were restricted in terms of their size (Jones & Howe 2005). The most recent Paralympic Games were in 2012 and held in London.

It should be noted that whilst the Paralympics and the Olympics are two separate sporting events in essence, crossover by athletes from disability to

able-bodied sport is allowed. Athletes who have partaken in the Paralympics and later the Olympics have included swimmer Natalie du Toit and table tennis player Natalia Partyka (Legg & Steadward 2011). In addition, archer Paola Fantato in 1996 and most recently runner Oscar Pistorius in 2012 participated in both the Olympics and Paralympics within the same year.

1.8.3 Classification Of Lower-limb Amputee Runners

To make disability competition as fair as possible, it was initially decided that athletes should be grouped into different 'classes' based on the type and extent of their disability (Bressan 2008). *Classification* can be defined as a single group of entities or units that are ordered into a number of smaller groups based on observable properties they have in common (Tweedy & Vanlandewijck 2009). Classification of a disability has been undertaken either as a specific designation of their disability, or more recently through actual functional assessment. Initially, classification was based on a medical opinion of the nature and extent of the disability. However, the process has evolved whereby a functional assessment is used to determine which classification an athlete is placed into for their competition (Tweedy & Vanlandewijck 2009; Bressan 2008). In some cases this could mean a non-amputee suffering a similar impact of disability would race alongside amputees - provided their impairment has a similar impact on performance (Bressan 2008) or a similar type of dysfunction (Jones & Howe 2005). Classification in this way is a current issue in disability sport (Depauw & Gavron 2005) and can have an impact on which athletes are successful (Tweedy & Vanlandewijck 2009). Classification was ultimately proposed to 'determine eligibility to compete' and to 'minimise the impact of the impairment on the outcome on the competition' (Bressan 2008).

As the philosophy for classification has changed, so too has any formalised reference or code for an athlete with a below-knee amputation. These codes have changed during the 1976-2012 timeframe and have been defined in each Paralympic Games as:

- *MC* (1976 & 1980)
- *A4* (1984 & 1988)
- *TS2* (1992)
- *T44* (1988-current)

The current classification system uses a letter and number based system to denote the events generalised context. For example, this can mean 'T' meaning track and 'F' meaning field based events. This is followed by a number which relates to the type of disability (Webster et al. 2001). The larger this number is, the smaller the severity of the disability (Bressan 2008). Lower-limb amputees who most commonly compete in short distance running events are typically 'T42', 'T43' or 'T44' types (www.paralympic.org). T42 refers to single (uni-lateral) above knee amputees. T43 refers to double (bi-lateral) amputees and T44 refers to uni-lateral below knee amputees. A T44 athlete is illustrated in figure 4.



Figure 4. T44 Athlete (www.lewisphoto.wordpress.com)

In the case of lower-limb amputees, a race with six T44 athletes and two T43 athletes would be generally listed as a T44 based event. However, medals at the Paralympic Games are awarded to the first three athletes across the finishing line of their event, not the first 3 of each classification type (www.paralympic.org/results). The Paralympic Games is currently capped at a maximum level of 4000 participating athletes. Whilst fewer classifications are desirable to make the sporting spectacle easier to understand, inaccurate or inequitable classifications could then be considered unfair competition (Howe & Jones 2006). In addition, the governing body has determined a minimum athlete participation level to allow an event to have its own disability category. In the case of insufficient participation, separate classifications can be grouped together.

1.8.4 Race Distances

Running distances for Paralympians have been adopted from standardised formats also used at the Olympic Games (Miller 2003). At the Paralympic Games, the same race distances are used. As a result, individual athletes with a lower-limb amputation have historically contested the 100m, 200m and 400m events for both males and females. However due to the IPC's participation requirements, not all of these have been participated in by both sexes at the Paralympic Games continually since 1976 (www.paralympic.org/results). However, there are accounts of athletes with amputations competing in able-bodied competition over longer distances or durations. These have included Amy Palmeiro-Winters competing in the marathon (Wolbring 2012) and Sarah Reinertsen competing in triathlon (Booher 2010).

1.8.5 Disability Sport Governance

Initially, governance at the Paralympic Games was undertaken by consulting with several smaller organisations, each with their own interest for a particular type of disability (Kioumourtoglou & Politis 2002, Legg &

Steadward 2011). Four of these later recognised the need to coordinate the Paralympics and in 1982 created an International Coordinating Committee Sports for the Disabled (ICC) (Gold & Gold 2007). This was driven in part by the Olympic Games governing body, the IOC wishing to correspond and collaborate with one umbrella organisation rather than several smaller ones (Legg & Steadward 2011). By 1989, the International Paralympic Committee (IPC) was formed (Kioumourtzoglou & Politis 2002) with its constitution and byelaws ratified in 1990 (Legg & Steadward 2011). The IPC now serves as the umbrella organisation for 162 National Paralympic Committees, five regional bodies and four international disability specific sports federations (Gold & Gold 2007). Both the Paralympics and the quadrennial World Championships for individual sports (such as swimming and athletics) are currently organised and managed by the IPC (Jones & Howe 2005). The IPC's formal headquarters were created in Bonn, Germany in 1999 where they continue to reside today.

The Paralympics held in 1988 used the same facilities and resources as the Olympics so have subsequently been considered to be the first of the modern style games (Legg & Steadward 2011). Cities which have sought to hold either the 2008, 2010, 2012 or 2014 summer or winter Olympics have also had to include the inclusion of the Paralympics and their specific needs within the same bid (Gold & Gold 2007).

1.9 CONCLUSION

The current format and governance of lower-limb amputee racing has been consistent since 1988 and lower-limb amputees have raced against each other since 1976. The alignment of the Paralympic Games to the Olympics should ensure the same stability of athletic format for the foreseeable future. The use of combined lower-limb amputee classifications when partaking in any running events warrants further investigation.

CHAPTER 2: TRANSTIBIAL AMPUTEE MOTION & PROSTHETICS TECHNOLOGY: A REVIEW

2.1 INTRODUCTION

This chapter reviews the history of both amputation and prosthetics. In addition, it assesses the research associated with lower-limb amputee running and sprinting and ascertains what issues are unresolved with respect to amputees, their prosthesis and disability sport.

2.2 A BRIEF HISTORY OF PROSTHESIS

The expression 'prosthesis' stems from the Greek word meaning 'addition' (Gutfleisch 2007). To help patients who have lost a limb due to amputation, use of prostheses is recommended to help them resume an active lifestyle (Gutfleisch 2003) or to replicate the missing anatomical structure (Hillery & Strike 2001). To this end, developments in prosthesis are directed towards improving comfort, reducing energy expenditure and improving stability (Gutfleisch 2003).

There is evidence that prostheses have been used for at least 5000 years (Gutfleisch 2003). An early example from this period included a toe prosthesis that had been carved from wood. Early examples of leg prosthesis were manufactured using techniques used for heavy armour (Gutfleisch 2003). In 3500-1800 BC, an early poem was written that concerned Queen Vishpla losing her leg in combat and then being fitted with an iron prosthesis before then returning to war (Cantos 2005; Thurston 2007). Prosthesis ultimately moved from the aesthetic to increased functionality when Ambroise Pare' (1510-90) designed prosthesis that provided a range of knee articulation (Cantos 2005). Later in 1805, James Potts filed a patent for an artificial limb that comprised an articulated foot. In 1816, Potts then built a limb for the Marquess of Anglesey who had lost their leg in the Battle of

Waterloo. This limb became known as the 'clapper leg' due to the noise it made upon reaching full extension (Gutfleisch 2003).

It has been claimed that war as an event has provided the main catalyst for prosthetic innovation (Cantos 2005; Coakley 2002; Guyatt 2001). Conflicts such as the American Civil War, the First and Second World Wars, and Vietnam all saw significant leaps in prosthetic innovation (Gutfleisch 2003). However, it is now proposed that increased population is also contributing to the need for improved prostheses development (Gutfleisch 2003).

The basic components of a modern lower-limb below-knee prosthesis are shown in figure 5.

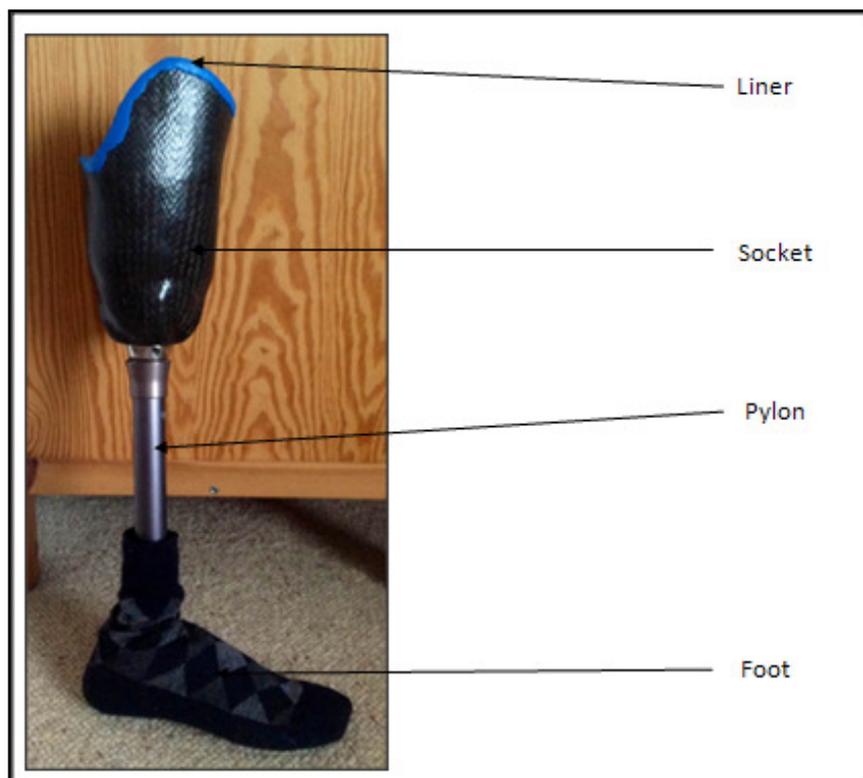


Figure 5. Typical Contemporary Prosthesis (www.sugru.com)

The typical below-knee prosthesis shown in figure 5 comprises a *Liner*, often made of a visco-elastic material (Lewis et al. 1996) such as silicon or gel (Webster et al. 2001) which then roll over the top of the residual limb. The liner helps to absorb torsion and shear forces, reduce sweat production and contribute to a good prosthetic fit (Powelson & Yang 2012; Lewis et al. 1996). The limb and liner is then inserted into the prosthetic *socket*. The socket is generally considered to be one of the most important components of a prosthesis due to its requirements (Powelson & Yang 2012; Laferrier & Gailey 2010) and this transmits the forces between the residual limb and the prosthetic itself (Powelson & Yang 2012). It has to achieve satisfactory load transmission, stability and efficient control of mobility. Due to the shape of the socket, the limb is suspended which prevents impact to the sensitive distal end. The limb is held inside the socket through means of suction and suspension designed to support the prosthesis when no weight is being placed upon it (Powelson & Yang 2012). Suction suspension itself was patented as an innovation in 1863 but not utilised frequently until nearly 80 years later (Harvey et al. 2012). Below the socket assembly is the *shank* or *pylon* (Powelson & Yang 2012) which contributes to providing the correct limb length. The shank subsequently then attaches to the foot assembly which can be shaped or derived from different materials depending on the user's needs and prostheses application (Powelson & Yang 2012). The dimensions of these parts depend on the needs, physiology and biomechanics of the intended user. The prosthesis ultimately requires adjustment in terms of alignment and this was made possible when German company Otto Bock introduced endoskeleton components in 1970 (Harvey et al. 2012). The other key requirement is the best possible fit of the socket as the limb stump is subjected to volume change. The fit of both socket and alignment is normally conducted by a prosthetist.

The development of specific prostheses for sport did not firmly take hold until the 1980's which was potentially caused by a fitness boom (Michael et al. 1989). The introduction of the Seattle foot in 1981 brought the introduction of energy storing prosthetic feet (Hafner et al. 2002b). This comprised a flexible

fibreglass keel housed inside a polyurethane shell (shaped like a foot) (Bragaru et.al 2012). In the mid 1980's, a running specific prosthesis designed for trans-femoral amputees was created known as the Terry Fox design which used a coiled spring shank design (DiAngelo et al. 1989). Later, a significant progression for both above and below knee amputees was made when Van Philips conceived the Flexfoot in 1987 (Hafner et al. 2002b). In the media these are sometimes referred to as 'Cheetah' legs (Zettler 2009; Curran & Hirons 2012) due to their resemblance to the hind legs of the animal which formed part of Van Philips inspiration. This design (later purchased by the Icelandic company Össur) is the basic principle of current energy return prosthesis technology seen in current disability running sport today and of those primarily investigated in this research project.

The Flexfoot© design comprises a flexible carbon fibre shank and heel spring and is often 'c' or 'j' shaped in profile. This was first seen on the market in 1987 (Hafner et al. 2002b) and in elite competition at the 1988 Paralympic Games (Nolan 2008). Four years later the prosthetic heel component was removed creating the first sprinting specific prosthesis in the guise that is currently recognisable today. This innovation allowed amputees to run faster (De Pauw & Gavron 2005, p.167). The prescription of such prosthesis is defined by the user's weight and activity level (Curran and Hirons 2012). The basic construction of a modern running prosthesis is shown in figure 6.



Figure 6. Sprint Running Prosthesis (www.mmajunkie.com)

It should be noted that prosthetics technology can be more complex and have greater levels of innovation than those witnessed in lower-limb amputee running. Clinical prostheses have seen innovations such as micro-processor controlled movements (Harvey et al. 2012) hydraulic knee actuators (Webster et al. 2001) or osseo-integration of bone to prosthesis connection (Harvey et al. 2012). At this time, such innovations are inherently expensive and not allowed for use in elite disability sport under its rules and regulations.

2.3 THE FUNCTION OF RUNNING PROSTHESIS

The modern running prosthesis has been termed *dynamic elastic response* (Geil et al. 2000) or *energy storage and return* (Hafner et al. 2002a) prostheses. In this thesis, the expression, 'energy storage and return prosthesis' (ESR) will be used. Such technology is typically prescribed to an athlete based on their bodyweight coupled with selection of the appropriate stiffness category (Lechler & Lilja 2008).

Modern ESR's are normally manufactured from a composite material (Nolan 2008) and are effectively a spring (McGowan et al. 2012, Lewis et al. 1996)

of a passive nature (Nolan 2008). As a result, such a design under load exhibits the characteristics of *energy return* (Nolan 2008) and *stiffness* (Jaarsveld et al. 1990). Mechanical losses in the form of heat, sound or friction will reduce the energy efficiency of the prosthesis (Nolan 2008). The energy efficiency of such designs has been reported to be approximately 95% but this only involved assessment under statically applied loads (Nolan 2008). Running is a dynamic activity and only a personal communication reported by Nolan (2008) provided any evidence of dynamic energy efficiency of ESR's whereby an efficiency of 63% was reported. As a result, any claims of efficiency may well significantly overestimate performance unless used in dynamic activity.

A fundamental difference when comparing biological lower-limbs to ESR's is that the human ankle has had a reported energy efficiency of 241% (Czerniecki et al. 1991) which suggests the human ankle can substantially enhance lower-limb energy and power production via its muscles and tendons. The ESR is unable to be more than 100% efficient seemingly putting it at a disadvantage when compared to the human foot region. Only active prosthetic components could correct for this difference (Hafner et al. 2002b) although additional performance enhancing characteristics may be hypothetically possible for amputee runners with bi-lateral amputations (Noroozi et al. 2012). ESR's are fundamentally a passive device (Nolan 2008). Energy efficiency has been calculated by method of functional testing (Michael 1987), mechanical analysis (Bruggemann et al. 2008), kinematic analysis using motion capture (Hafner et al. 2002b) and mathematical analysis (Prince et al. 1998). A comparison using two kinetic analysis methods has been undertaken but provided a lack of correlation in terms of efficiency and energy return between them (Geil et al. 2000).

Mechanical stiffness of ESR's is relevant as high levels of lower-limb stiffness are evident in running (McGowan et al. 2012) and has been correlated to maximal sprinting performance in able-bodied persons (Chelly

& Denis 2001). High stiffness is therefore desirable but needs to be defined in uni-lateral amputees by the apparent stiffness of the biological limb as limb to limb symmetry has been proposed to improve overall performance (Nolan 2008).

The question therefore is whether performance enhancement is a valid issue at all with lower-limb prostheses design. Adopting Buckley's' (1999) observation that a lower-limb running prosthesis could need to be 'tuned', some focus has been placed on the adjustment qualities of the lower-limb running prostheses. This has been achieved by adjusting its placement of the knee joint asymmetrically (Burkett et al. 2001) and placement of mass on a LLP (Selles et al 2004; Trabelsi et al. 2005). These studies both showed differences in biomechanical asymmetry, energy return efficiency, gait patterns and the users metabolic cost. However, it was shown that there was considerable scope to investigate and optimise the effects of inertia and centre of mass at sprinting speeds (Nolan 2008). These studies indicate (along with the acknowledgement that the energy return prosthesis does not physically resemble the human limb), that an aesthetically non-biological or an asymmetrical functioning prosthesis may be a more effective design solution to lower-limb disability running. Demand for optimisation may exist and a patent was ultimately lodged regarding tunable prosthesis (US Patent No. 7211115).

No research at this time has shown that the modern prosthesis is able to outperform the respective human limb when judged in isolation from the rest of the human body, but several studies have shown that variation in performance such as energy transfer exist between clinical prostheses designs themselves (Michael 1987; Prince et al. 1998; Thomas et al. 2000; Barth et al. 1992) and in the composite lay-up prescriptions of ESR's (Lechler 2005). There are concerns that the full understanding of such technology may never be known (Nolan 2008). However, the need to maximise performance of such technology is obviously desirable by the prosthetist and/or the athlete.

2.4 TRANS-TIBIAL AMPUTEE RUNNING

2.4.1 Lower-limb Amputee Running: A Background

Enoka et al (1982) published one of the earliest pieces of research to investigate below-knee amputee running gait. He demonstrated that a degree of asymmetry and loading imbalances existed between a prosthetic and a sound limb. Due to the limitations (or possibly the limitations of the prosthesis design at that time), the speeds his ten test subjects could achieve was 4 m/s which in modern terms is approximately half that of current typical amputee sprinting speed (Nolan 2008).

Running specific speeds were later addressed within Lewis et al. (1996) research. This work sought to increase the understanding of both amputee and prostheses behavior when subjected to higher speeds than previously attempted. In addition, the study used athlete test subjects whose inclusion in studies had been extremely limited up until this point. This paper was very much an extension of Czerniecki and Gitter's (1992) muscle work analysis of amputee running and co-author John Buckley later extended this into a more specific context of amputee *sprinting* (Buckley 1999; Buckley 2000). Buckley noted that the needs of the individual athlete with a disability were such that it may require prostheses to be individually 'tuned' to obtain the best possible running gait. This ultimately starts to address the individual needs of lower-limb disability running technology and demonstrates that a much more tailored approach is needed to optimise the activity.

With the inception of ESR's, the differences between able-bodied and amputee test subjects were evaluated (Czerniecki et al. 1991). These have been investigated when *walking* (Prince et al. 1998; Barth et al. 1992) and *running* (Prince et al. 1992; Czerniecki, Gitter and Beck 1996; Thomas et al. 2000). The outcome of these demonstrated both biomechanical and efficiency based differences in uni-lateral amputees and that the human limb performs better both in their resultant ground reaction forces and energy return efficiency. These studies therefore propose that in the case of a uni-

lateral amputee, the LLP is inferior to that of a human leg when using current technology although these views were challenged more recently with analysis of a bi-lateral amputee (Bruggemann et al. 2008).

Recent published literature reviews have focused on prostheses technology mechanical differences to the sound limb in amputee running (Nolan 2008), a framework of lower-limb kinematic and kinetic characteristics (Pailler et al. 2004) and a review of the technology currently employed within running sport (Webster et al. 2001). However, whilst studies have evaluated lower-limb amputees at a variety of speeds, most studies use steady state running speeds to assess test participants. This means the variable speeds evident in races such as the 100m or 200m is not considered. In addition, the track that athletes compete on comprises two straights and two bends per 400m lap. Whilst some evaluation has been undertaken to ascertain changes in lower-limb stiffness when running, it is not known of what changes occur to lower-limb kinematics and biomechanics with trans-tibial amputees running round these bends. Research focusing on competitive amputee runners appears to be seeing continual increases in specificity but still lacks the full characteristics of the actual event competed in.

2.4.2 The Biomechanics & Kinematics of Amputee Running

The biomechanics of amputee limbs when running are divided into a limb 'stance' and 'swing' phase (Umberto et al. 2006; Gailey 2002). During stance phase, the initial contact to mid stance by a limb is referred to as the 'absorption phase' (Umberto et al. 2006; Gailey 2002). The mid stance to toe-off period is known as the propulsion phase. This is whereby a single lower-limb generates thrust and the body generates the acceleratory forces that are carried over as the other limb begins to swing through (Gailey 2002). The beginning and end of each swing phase will see a small duration whereby neither limb is in contact with the ground. An illustration of amputee running as defined by Gailey (2002) is shown in figure 7.

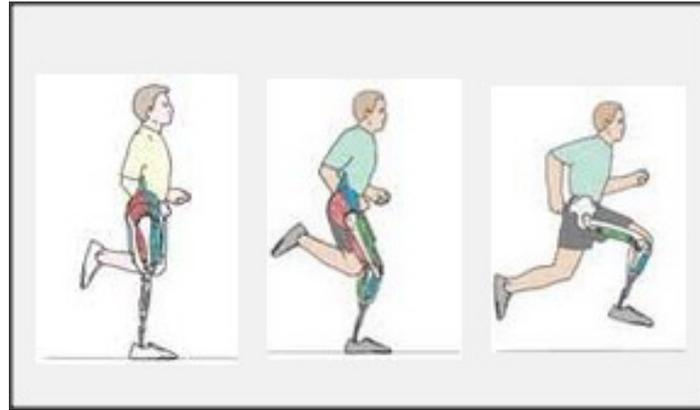


Figure 7. Amputee Running. From left to right: 'stance' phase, 'absorption' phase and 'swing' phases (Gailey 2002).

It has been proposed that the stance phase accounts for less than 50% of the running gait cycle. As speed increases, the percentage of the stance phase decreases (Gailey 2002). The combination of the limb swing and limb stiffness determine the ground contact time which has been proposed to be an important variable that dictates maximum running speed of the amputee (McGowan et al. 2012).

The sprint kinematics of both the hip and the knee has been shown to be similar in both biological and artificial lower limbs (Buckley 1999). In addition, the hip has been shown to be the main compensatory effect by an amputee during stance with increased work at the knee and hip during swing (Sadeghi et al. 2001a; Czerniecki et al. 1996). Increased work at the hip during stance has been also witnessed in a small number of trans-tibial amputee sprint athletes (Buckley 2000). Lower-limb propulsion is proposed to be lower on the amputated limb in uni-lateral amputees (Sadeghi et al. 2001a).

2.4.3 Amputee Running & Lower-limb Symmetry

Biomechanical asymmetry has been shown to exist in amputee running (Buckley 1999; Buckley 2000; Enoka 1982) but has been indicated to be affected by the level of disability and the prosthesis employed (Czerniecki, Gitter & Beck 1996).

Lower-limb symmetry itself has been remarked as desirable in running gait (Nolan 2008) and often assumed in literature (Sadeghi et al. 2000). The calculation of lower-limb to limb symmetry has been shown to be problematic due to the intra-limb variability being greater than the proposed limb differences (Exell et al. 2012). However, such concerns are levelled at the assessment of able-bodied candidates, not those with lower-limb amputations which would be less inclined to be as symmetrical.

In trans-tibial amputee sprinting, there have been observations that typical asymmetry exists in stance and swing phase ratio's and for step lengths (Lewis et al. 1996). The pursuit of symmetry specifically may not be the answer to a more effective prosthesis design (Burkett 2001) or as important as understanding any compensation strategies (Sadeghi et al. 2001b). Studies with able-bodied participants have indicated that a natural asymmetry does occur between the lower-limbs and may also include the impact of any lower-limb dominance known as 'laterality' (Sadeghi et al. 2000). It is not known what role laterality has at faster locomotion speeds such as those witnessed in competitive running but it has been remarked that use of prostheses does change any impact of laterality (Taylor et al. 2006).

The measurement of symmetry can be performed merely by comparing performance metrics from one side to another. However, statistical methods such as the *symmetry indices* (Karamanidis et al. 2003) or the *symmetry angle* (Zifchock et al. 2008) have been demonstrated to be reliable metrics to specify limb-to-limb imbalances. However, symmetry indices have been shown under certain conditions to artificially inflate results (Exell et al. 2012). A composite method using several metrics has been shown to hopefully reduce this issue but either way, it is proposed that inter-limb differences must be greater than intra-limb variability (Exell et al. 2012).

2.5 CONCLUSION

Research into lower-limb amputee running is still in a state of relative infancy. The specialisation of its prosthetics technology is only approximately 30 years old. The current ESR technology used has only been in service in competitive sport for 25 years. Research into high speed running performed by athletes with a trans-tibial amputation has only been evident for the last 14 years and the most detailed holistic evaluation is only 5 years old. This is a relatively short period to expect a thorough understanding of amputee running. Case studies or very small numbers of amputees are typically evaluated in the studies that exist which make any findings limited. As a result, event discipline differences such as duration, length or characteristics are still not yet considered in empirical research.

CHAPTER 3: SPORTS TECHNOLOGY: A REVIEW

3.1 INTRODUCTION

This chapter reviews the use of technology in sport, its implications and an assessment of criteria used to formulate debate on its inclusion. Some of this chapter's content has seen peer review via journal publication (Dyer et al. 2010) and is contained within Appendices F.

3.2 SPORT TECHNOLOGY INCLUSION

Sports technology and subsequent discussion surrounding potential performance enhancement has included *artifact* (Dyer 2010; Holowchak 2002; Kyle 1991), *material* (Stoll et al. 2002; Froes 1997), or *chemical technologies* (Savulescu et al. 2004; Miah 2005; Gardner 1989). Pursuing optimised sports technology is valuable when it has been proposed that based upon within-event athlete performance variability, any statistical performance improvements for able-bodied track athletes can be as small as 0.3-0.5% to still be deemed worthwhile (Hopkins 2005).

The field of study that surrounds the decision making or debate with respect to the actual acceptability, inclusion, or controversy of sport technology has been termed performance *enhancement* (Loland 2009), *technosport* (Freeman 1991) *human enhancement technologies* (James 2010) or *mechanical ergogenics* (Holowchak 2002; Kyle 1991). Whilst this designation may differ, there appears to be no difference between the various titles scope.

The means to determine a physical sports technology or equipment's viability and validity has attempted to be resolved using ethical discourse. The starting point for such discussion has included being *prior to a technology's*

adoption (Miah 2000), debate of a *technology in service* (Hilvoorde 2010; Holowchak 2002; Magdalinski 2000) or debate surrounding the *illegal use of sports technology* (Hemphill 2009). It has been argued that the adoption of sports technology needs an 'ethical foundation' rather than an acceptance of an attitude to win at any cost (Freeman 1991). However, a shortcoming of resolving the use of sports technologies can be strongly opposing views, despite well constructed arguments. For example, with the debate surrounding performance enhancing drugs, ethical discourse produced views that were either pro-doping (Foddy & Savulescu 2007; Savulescu 2006) or anti-doping (Wiesing 2011; Lavin 2003). This means the use of philosophical discourse cannot guarantee moral consistency although this disparity has been recommended to be overcome by means of obtaining consensus directed from a point of authority (Sakine & Hata 2004). What sports philosophy can do is to identify values whilst establishing the soundness of any arguments (Hemphill 2009).

Quantitative methods have also been used to determine the impact and viability of sports technology inclusion and these have included *economic feasibility studies* (Osborne 2005), *mathematical modelling* (Haugen 2004) and *legal analysis* (Zettler 2009; Shapiro 1991). *Empirical testing* has been used as evidence to prescribe the acceptance level of performance enhancement (Weyand & Bundle 2009; Kram et al. 2009) but typically scientific studies present findings related to the performance of sports technology as opposed to then arguing for its inclusion/exclusion. Both qualitative and quantitative methodologies typically use one of the techniques listed but it is not known whether a mixed method or comparative approach would be superior approaches.

3.3 SPORT TECHNOLOGY CONTROVERSY

There are several case studies within sport of controversy surrounding sports technology already adopted for use. Some examples of these are illustrated in figure 8.



Figure 8. Sports Technology ControversyExamples

The examples in figure 8 include (from top left and clockwise), the Speedo Speedsuit swimsuit, Ossur Cheetah Prosthesis, the Polara Golf Ball and Graeme Obree's 'Old Faithful' bicycle.

A summary of case studies taken from reviewed literature is shown in table 2.

Table 2. Case Studies of Sports Technology Controversy

Sports Technology Innovation	Controversy
Pole Vault: Composite Pole	<ul style="list-style-type: none"> - Sudden increase in world records (Haake 2009). - Last minute ban altered athlete preparation (Millar 2003, p201).
Tennis: String Patterns ('Spaghetti Stringing')	<ul style="list-style-type: none"> - Allowed a player to generate more power and greater accuracy. (Gelberg 1998). - The new design saw many lower ranked players suddenly gaining the ability to beat higher ranked ones who had not had access to the new rackets (Gelberg 1998).
Swimming: 'Speedsuits'	<ul style="list-style-type: none"> - Only Speedo sponsored athletes had access to technology (Burkett 2011). Only 5% of male finalists had access to this type of suit (Neiva et al. 2011).
Powerlifting: Squat Suits & Knee Straps	<ul style="list-style-type: none"> - Technology has increased performance but not increased interest in sport (Holowchak 2002).
Golf: Use of 'U Grooves' with the Sand Wedge club	<ul style="list-style-type: none"> - Increased ability to clear golf ball from bunker (Gardner 1989).
Golf: The Polara Golf Ball	<ul style="list-style-type: none"> - Reduced hook/slicing of golf ball (Gelberg 1998).
Track Athletics: Lower-limb prosthesis use by disability runner	<ul style="list-style-type: none"> - Use of a prosthetic lower-limb being advantageous over a biological lower-limb (Howe 2011; Magdalinski 2009).
Endurance Sport: Use of Altitude Tents	<ul style="list-style-type: none"> - Provides higher red blood cell count to an athlete by non-natural generation (Loland & Murray 2007; Spriggs 2005).
Speed Skating: The Clapskate speedskate design	<ul style="list-style-type: none"> - Sudden increase in world records (Hilvoorde et al. 2007; Koning et al. 2000).
Fencing	<ul style="list-style-type: none"> Rigging of sword to register an hit on the opponent by the attacker (Millar 2003)

This listing does not likely cover every historical case of sports technology controversy. Even so, even if it did, it has been noted that further controversy with sports engineering is inevitable since engineering as a practice involves

advancement of technology (James 2010). When considering the case study examples in table 2, such implementations have common themes such as how the sport is perceived or played (Gardner 1989; Miah 2006), made the sport easier (Sheridan 2006) or created issues when accessing technology with equal opportunity (Burkett 2011). These themes have also been used within qualitative methods and are typical in sports ethics discourse (Miah 2005). The qualitative themes used for arguing the inclusion or viability of sports technology and their subsequent issues surrounding performance enhancement are summarised in table 3 below.

Table 3. Summary of Sports Ethics Literature Review

Criterion	References
Harm or health (to the athlete or others)	(Hemphill 2009; Kayser et al. 2007; Miah 2006; Lavin 2003; Morgan 2003; Loland 2002; Stoll 2002; Bjerklie 1993; Brown 1980)
Un-naturalness	(Hemphill 2009; Miah 2006; Loland 2002; Stoll 2002)
Unfair advantage or consideration of fairness	(Murray 2010; Hemphill 2009; Carr 2008; Miah 2006; Lavin 2003; Stoll 2002; Loland 2002; Gardner 1989; Brown 1980)
Coercion	(Lavin 2003; Gardner 1989)
Safety, and spectator appeal	(Gelberg 1998)
Integrity of the game, harm to or advantage over the sport itself, or the 'spirit of the sport'	(Wiesing 2011; James 2010; Morgan 2003; Miah 2000; Gardner 1989; Feezell 1988)
Deskilling & reskilling	(Miah 2006; Sheridan 2006; Miah 2000; Gardner 1989)
Dehumanisation	(Miah 2000)
Cost (or excess cost)	(James 2010; Froes 1997)
The internal goods of a sport	(Schneider & Butcher 1995)
Equal opportunity or access	(Lenk 2007; Gelberg 1998)

A critical shortcoming of such criteria is knowing when or how to rank or prioritise them when more than one is applicable – especially if they conflict. For example, if a prosthetic device improves the safety and comfort to its user but alters the way the athlete runs in the event, such research typically rely on the sports ethicist or philosopher to subjectively rank or prioritise the value of such technology.

In the case of performance enhancing drugs, there has been support as to their legalisation when using some of the criteria in table 3 (Kayser et al. 2005; Savulescu et al. 2004; Brown 1980). Likewise, other researchers when using the same criteria have argued on behalf of upholding the ban (Schneider & Butcher 1995). As a result, this demonstrates that despite many key themes being consistent, ethical debate alone is not consistent enough to seek objective resolutions on sports technology inclusion.

3.4 DISABILITY SPORT TECHNOLOGY CONTROVERSY

Whilst there are several occurrences of issues surrounding sports technology inclusion in able-bodied sport, disability sport has seen fewer such cases. Despite this, there are some published case studies of elite athletes who have competed either in disability sport or have attempted to use their assistive devices in able-bodied sport that have created controversy.

3.4.1 Casey Martin

American Casey Martin was a professional golfer during the mid to late 1990's. Martin was a registered disabled citizen who suffered from a circulatory disorder in his lower right leg yet participated at an elite level on the PGA national tour (Charlish & Riley 2008). Golf carts were banned in professional golf at the time as it was felt that such technology would change the nature of the game by reducing the impact of the walk between and during each hole (Charlish & Riley 2008). Such use of technology can be interpreted from the PGA's position as being an *advantage over the sport* (Gardner 1989).

Martin contacted golf's governing body with the view to having the rule changed but the PGA refused (Charlish & Riley 2008). As such, Martin

attempted to force such a change through use of the American legal system and its current disability equality laws (Silvers & Wasserman 2000). The supreme court ruled that the walk aspect during the game of golf was not considered part of the sport and therefore ruled in Martin's favour in 1998 (Silvers & Wasserman 2000).

3.4.2 Oscar Pistorius

South African, Oscar Pistorius (figure 9) is a bi-lateral below-knee amputee who won gold medals in the 2004, 2008 (Jones & Wilson 2009) and 2012 Paralympic Games and is a World Record Holder (Camporesi 2008; Wolbring 2008).



Figure 9. Oscar Pistorius

As the result of a congenital defect, he was born without fibulae bones (Lippi 2012). His legs were amputated when he was 11 months old (Edwards 2008). Pistorius wanted to participate in able-bodied athletic competition despite his disability. Approaches in literature to resolve or clarify his case have taken a *scientific* (Bruggemann et al. 2008), *philosophical* (Edwards, 2008) or a *legal* basis (Charlish & Riley 2008; Wolbring 2008).

During late 2007, Pistorius signalled his intentions to qualify for both the 2008 Paralympic and Olympic Games (Edwards 2008; Jones & Wilson 2009) based upon finishing second at the 400m at South African National Athletics Championships (Charlish & Riley 2008) or possibly due to coming 2nd in a Golden League track (Mokha & Conrey 2007). Pistorius uses energy return lower-limb prosthesis currently legal for use in IPC governed events. However, the governing body of able-bodied athletics, the IAAF, argued that the use of such technology contravened its rule 144.2 which forbade the use of 'a technical device which uses 'springs, wheels or any other element that provides the user with an advantage over another athlete not using such a device' (Jones & Wilson 2009). Whilst ESR's are sprung devices, it was argued that this rule was not specifically intended to prevent participation by the disabled (Mokha & Conrey 2007) nor was it known at the time if such technology was actually advantageous. In response, the IAAF commissioned research to ascertain whether any advantage existed (Jones & Wilson 2009). The results of this research proposed that ESR's manifest advantages over able-bodied participation. These include an increase in energy efficiency of upto 25%, the provision of three times the energy return than a human ankle joint and finally, providing a mechanical advantage in relation to a healthy ankle joint of more than 30% (Bruggemann et al. 2008). However, this research did not consider the many phases of a sprint event such as the acceleration from the starting blocks, running the bends, or any other additional disadvantages Pistorius felt he personally had (Jones & Wilson 2009). In addition, the research evaluated Pistorius himself as a sole case study rather than as a sample population of bi-lateral amputees (Bruggemann et al. 2008). As a result of this, any empirical findings may be because of Pistorius skill rather than as a trait of the bi-lateral amputee athlete community. It was also reported that the type of athletes used as a baseline that Pistorius himself was compared against were defined as 'elite'. The Bruggemann et al. study (2007) used typical 400m finishing times of the test subjects to define this. It is contentious whether this key performance indicator is the one that should be used. Even if this was the case, any

decision from the IAAF rested on findings based on tests tailored to the needs of the 400m event despite that the physiological needs of the shorter 100m event were not considered. Any decision to ban Pistorius from able-bodied competition seems to have ultimately been based on incomplete empirical information.

The decision to initially ban Pistorius based was challenged. A legal evaluation using the basic principles of justice have argued that he should have been cleared to run immediately (Charlish & Riley 2008). A philosophical exploration of what it means to be disabled or whether he has an unfair advantage on a philosophical level have also supported this (Edwards 2008). It has been argued that an advantageous characteristic is the same for any elite level athlete (Edwards 2008). His prosthesis, even if advantageous, were argued to be no different in essence to an Ethiopian distance runner living at altitude having an increased red blood cell count to improve their aerobic abilities. The critical distinction here though is that Pistorius prosthesis are manufactured and therefore not naturally obtained. Either way, the IAAF upheld a ban based upon the evidence provided in the Bruggemann et al. (2007) study.

Some months later, a study commissioned in the USA argued that in fact Pistorius did not have any advantages (Weyand et al. 2009). In the result of conflicting arguments, the Court of Arbitration for Sport overturned the IAAF's ban (Camporesi 2008) therefore clearing Pistorius to take part in his bid to qualify for the Olympics. In the end, Pistorius failed in his bid by only achieving the prerequisite time for the 400m once rather than the necessary twice. However, he did later achieve selection and participated in both the 400m and the 4x400m relay at the 2012 Olympic Games. The Pistorius controversy was a landmark case because the nature of disability or the consideration that someone disabled could be advantaged was not previously unheard of. However, Pistorius himself was beaten in the 2012 Paralympic Games 200m final by Brazilian Alan Oliveira

(www.paralympic.org/results). Oliveira is, like Pistorius, a bi-lateral below-knee amputee. It would seem that the acceptability of prosthetics technology in able-bodied competition is potentially an area urgently requiring attention, especially as Pistorius is no longer the only amputee with the potential to crossover to able-bodied sport, let alone the potential of other types of athletes with a disability such as above-knee amputees.

Despite this case study not being centred within disability sport, the key issue that this highlights is a lack of a comprehensive understanding of the nature and regulation of prosthesis as well as the functional differences when comparing biological to artificial limbs.

3.5 SPORT TECHNOLOGY REVENGE EFFECTS

Once a technology has been determined to be included, a secondary, indirect or negative effect has been proposed to sometimes occur (Tenner 1996). This has been proposed as the 'Revenge Effect' and acts as a 'Paradox of Improvement'. Case study examples of this are listed in table 4.

Table 4. Case Studies of Sports Technology 'Revenge Effects'.

Sports Technology Innovation	Controversy
Amateur Boxing: Protective Headgear	Increase in head injuries caused by boxers feeling they have an increased invulnerability (Miah 2005; Tenner 1996).
Tennis: Racket Head Size Increase	Impact of rallies reduced. Ball pressure had to be changed to compensate (Savulescu 2006)
Field Athletics: Javelin material change	Safety of officials at risk due to javelins increasing throw length. Javelins centre of gravity altered to compensate (Froes 1997).
Track Athletics: Lower-limb running prosthesis	Technology defined as advantageous over non-disabled participants (Bruggemann et al. 2008).

As a result, the repercussions of a sports technology inclusion can have wider repercussions that could inadvertently create some of the arguments listed in table 3.

3.6 SPORT TECHNOLOGY ACCEPTABILITY FRAMEWORKS

Whilst moral discourse often uses selected criteria chosen by the author to determine technology's inclusion, an extension to ethical or moral discourse is whereby performance enhancement scenarios are judged against structured frameworks to determine whether such an enhancement is acceptable. The suitability of those in published literature are evaluated when considering LLP's for their suitability.

Gardner (1989) defines a four point framework to help structure ethical discourse to determine acceptable performance enhancement. He defined an enhancement as inappropriate for use in sport if it caused:

- harm
- coercion
- unnaturalness
- an unfair advantage

This framework considers the result of the technologies inclusion rather than considering the actual intent behind the technology's introduction. Artificial limbs are by their very nature not natural products and also essential to perform the act of running therefore these criteria is too limited in its scope. Prosthesis use in competition has also been reported to cause injuries when under competitive conditions (Nyland et al. 1999). As such this framework is not suitable for use when evaluating current ESR technology.

Miah (2005) later summarised several ethicist's attempts to structure ethical discourse by providing an expanded framework from that of Gardner's. Miah's six point framework for determining sports technology non-inclusion:

- 1) *Technology that makes sport possible.*
- 2) *Technology that affect safety and harm.*
- 3) *Technology that de-skills or re-skills sport.*
- 4) *Technology that dehumanises performance.*
- 5) *Technology that affects participation and/or spectatorship.*
- 6) *Technology that has a negative, secondary effect on a sport.*

Miah's framework is more comprehensive but still retains the issues of Gardner's proposal. This is now compounded if prosthesis technology is intended to restore function via any means of enhancement. Under this scenario, such technology would also arguably de-humanise sport. The best prosthesis technology can hope to do is to simulate any lost limb. Yet the nature of ESR's does not achieve this functionally or aesthetically as they have no ankle joints.

When specifically regarding chemical performance enhancement specifically, the World Anti-doping Agency (WADA) regulates and polices the use of such technology (Foddy & Savulescu 2007) and later implemented a code to define acceptability (Miah 2006). A chemical sports technology product may be designated as illegal if it infringes any 2 of its 3 core criteria. As such, an enhancement shall be judged illegal if it:

- Is detrimental to the health of an athlete.
- Is deemed performance enhancing.
- Violates the 'spirit of sport'.

The first two criteria of the WADA framework are as per Miah's previous proposal in that prosthesis could be infringing conditions of enhancement or health. The last term is highly ambiguous. The subjectivity of the term 'spirit of sport' has been attempted to be classified by Loland & Murray (2007). Products which are determined to fail the framework are then added to a list of banned methods. Such a list is useful. However, the ability of this framework would be limited if when applied to sports equipment like prosthesis that would need to be tailored to the individual (Nolan 2008). As such, this framework is not specific enough to the prosthetics context.

Loland (2009) took an alternative approach to determining performance enhancement acceptability by providing a model for 3 ethical belief systems to be utilised by a sport. His model was described as 'ideal-typical normative' views of technology and were defined as:

- The 'Relativist' theory – that technology is acceptable if it provides the opportunity for prestige or profit.
- The 'Narrow' theory – that any technology is acceptable to help take us to our natural conclusion – the absolute maximisation of human performance using all technology available to achieve it.

- The 'Wide' theory – that sport has meaning beyond that of the athlete's performance and in addition that athletes are moral agents. As such, regulations with respect to technology are essential.

Such a model is advantageous as it effectively encourages the governing body to reconsider its policy to sports technology at a fundamental level. The issue with such ideological models such as Loland's, is that it glosses over the resultant (and varied) impacts of technology in different sports.

Ultimately, Loland's model would be suitable as a starting point for a rewritten framework, provided the identified stakeholders adopted one of its options.

3.7 LEGISLATION OF LOWER-LIMB PROSTHESES IN DISABILITY SPORT

The legislation of LLP's is overseen and defined by the IPC. Such legislation is a series of evolving constraints that are periodically reviewed. The current rules dictating prosthesis use were updated during the course of this research project. It should be disclosed at this point that the author was part of an IPC working group from 2009-2010 that contributed to discussion with respect to rule amendments regarding prosthesis use in athletics. This section will review the rules and analyse the limitations of them.

The rules regarding prosthesis are contained within the 'IPC Athletics Rules & Regulations (IPC 2012). The philosophical underpinning of technology's use in disability sport as defined in the IPC Rules & Regulations 2011-12 from page 12-14 are summarised in figure 10.

3.3 Technology Equipment

3.3.1 Fundamental Principles

The fundamental principles that IPC Athletics is promoting regarding the evolution of equipment used during Recognized Competitions are:

- a) Safety (i.e., to the user, other competitors, officials, spectators and the environment);*
- b) Fairness (i.e., the athlete does not receive an unfair advantage that is not within the “spirit” of the event they are contesting);*
- c) Universality (e.g., reasonably commercially available to all);*
- d) Physical Prowess (i.e., human performance is the critical endeavor not the impact of technology and equipment).*

Note: The IPC is currently investigating ways to define and regulate equipment in order to secure the above goals and to establish valid and reliable methods for testing equipment to ensure that it complies with the above fundamental principles and any other regulations laid down.

These principles apply in particular (but not exclusively) in relation to the development of:

- a) Sports specific prosthesis;*
- b) Specification for Throwing Frames and materials for Holding Bars;*
- c) Wheelchair componentry.*

3.3.2 Monitoring of the Use of Technology and Equipment

The IPC Athletics Technical Delegate, or his designee, will monitor the use of technology and equipment at IPC Athletics Recognized Competitions to ensure that it conforms to the principles outlined in

3.3.1 above. This monitoring may include the assessment of (but will not be limited to):

- a) Unrealistic enhancement of height of release in throwing events;*
- b) Unrealistic enhancement of stride length;*
- c) Whether or not equipment and/or prosthetic components are commercially available to all athletes (i.e., prototypes that are purpose built by manufactures exclusively for the use of a specific athlete should not be permitted, and;*
- d) Whether equipment used contains materials or devices that store, generate or deliver energy and/or are designed to provide function to enhance performance beyond the natural physical capacity of the athlete.*

3.3.3 Prohibited Technology

Use of the following technology is prohibited at IPC Athletics Recognized Competitions:

- a) *Equipment that breaches the above fundamental principles;*
- b) *Equipment that results in athletic performance being generated by machines, engines or robotic mechanisms, and;*
- c) *Osteo-integrated prosthesis.*

At any Recognized Competition the IPC Athletics Technical Delegate shall be entitled to prohibit the use of equipment prohibited by these Regulations and he shall in every case of a suspected breach (whether the equipment is in fact prohibited or not) report the matter to the IPC Athletics Sport Manager. Upon receiving such a report the IPC Athletics Sports Manager should refer the matter to the Sports Technical Committee and the IPC Medical & Scientific Director for further investigation and action on a case-by-case basis. The STC shall be entitled to prohibit the use of equipment either permanently or on a temporary basis (to allow for further investigation) where it considers, acting reasonably, that any of the fundamental principles of equipment design and availability are breached.

Figure 10. Technology Regulations

The core principles of *safety, fairness, universality* and the *physical prowess* of the athlete are the key fundamental philosophical criteria listed by the IPC. These echo those listed in table 3. These are also subjective expressions but the IPC does attempt to clarify the meaning of these. However, these explanations use further ambiguous descriptors such as ‘unfair advantage’. Likewise, it is also not known what ‘reasonably available to all’ means. Is this defined by access to a prosthesis or the cost of it? Additionally it also states that the emphasis is on the athletes ability, not on the prosthesis technology used. This suggests the prosthesis design is a *restorative* agent (Lavin 2003) or an act of *therapy* (Miah 2005) which is unlike general sports equipment which would be *additive in nature* (Lavin 2003). Yet these rules are also stated to apply to racing wheelchair events which currently use disc wheels and allow aerodynamic helmets for its athletes. Bearing in mind the importance of aerodynamics of sports technology when in motion (Kyle 1991) it would seem that the current norm does not follow these guidelines and that it is unclear whether this technology complies with the need for universality the IPC requests. If wheelchairs are non compliant,

the associated norms with disability technology seem to be set at quite a high level.

Section 3.3.2 in figure 10 details the thresholds of performance of LLP's. The criteria covers what constitutes an advantage but does not detail objectively what an 'unrealistic enhancement' or what 'natural physical capacity' is. As it stands, the only criteria specifically defined by the IPC is the length of the prosthesis itself. This suggests more objective measures are required to help define the nature and role of the prosthesis.

Section 3.3.3 in figure 10 covers banned technology or surgical procedures, which include newer procedures such as osseo-integration. Such a procedure reduces the emphasis on socket fit therefore making prosthesis use more comfortable. This, like the ethic based discourse reviewed in chapter 3 creates moral conflict involving an athlete's health. It is not clear if increased health or risk to a small number of athletes is more valuable than fairness to the sport as a whole.

Prostheses must be used by athletes performing track running as summarised on page 40 of the IPC's rules and regulations. These are shown in figure 11.

Prosthetics & Orthotics

10. For Sport Classes T/F35-38 & T/F42-46 athletes may wear a prosthetic/s or orthotic/s in order to ensure both legs are of equal length but not for any other purpose, and they must not otherwise provide assistance to the athlete.

11. Prosthetics Compulsory for T42-44 Track Events.

In track events athletes in Sports Classes T42-44 must use leg prostheses. Hopping is not allowed in track events.

Figure 11. Prosthesis Rules

These rules would seem to outlaw ESR's for use in disability sport. An ESR is a sprung device which does provide some level of energy return (Nolan 2008). As such, it provides performance assistance beyond merely providing stability when either standing or running. In addition, this contribution cannot be normalized as it was indicated in the review in section 2.3 that different ESR's produce different mechanical performance. As such, rule 10 would seem to infer that ESR's are the accepted norm.

To determine the length of the prosthesis used by an athlete, article 3.2.10.10 of the 2011 IPC Classification Rules & Regulation is used (IPC 2011) and is shown in figure 12.

3.2.10.10 Determining prosthesis length for lower limb amputees

The following rules apply to the length of prostheses used by lower limb amputees . Athletes with either unilateral above knee or unilateral below knee amputation can use a prosthesis for competition purposes which will result in the amputated side being longer or shorter than the functional length of the non-amputated side.

The length of prostheses used by athletes with bilateral lower limb amputations (bilateral below knee amputees, bilateral above knee amputees or combination unilateral above knee and unilateral below knee amputation) will be determined using the 3-Step process described below.

Step 1: Estimate maximum standing height from Ulna length.

Measure the distance between point of the elbow (olecranon process) and the ulna styloid using the technique depicted in the figure below. Measurement technique for ulna length. The maximum standing height in metres is determined from the chart below.

Step 2: Estimate maximum standing height based on measurement of demi-span.

Demi-span is measured as the distance from the middle of the sternal notch to the tip of the middle finger in the coronal plane. The measure is best obtained with the athlete standing with their back against a stable wall, right shoulder abducted to 90° with the palm of the hand facing forward. Maximum standing height is then calculated from the following formulae.

Females: Height in cm. = (1.35 x demi-span (cm)) +60.1

Males: Height in cm. = (1.40 x demi-span (cm)) +57.8

• Step 3 - final estimate of maximum standing height.

Take the mean of the two estimates, maximum standing height estimated from ulna length and maximum standing height estimated from demi-span. The overall standing height of the athlete with their competitive prostheses on must be less than or equal to the mean estimated height plus 2.5% . the maximum standing height will be kept on permanent record in the IPC Athletics Sports Management Data System (SMDS) database 3.2.10.12 It will be a matter of technical routine that all athletes with double lower limb amputations who compete standing up will be measured either before the competition starts, or in the call up room prior to the event or after the event the athlete has competed in. The measure obtained must at all times be less than the maximum standing height on the SMDS.

Figure 12. Limb Length Regulations

The calculation for limb length uses a quantifiable method coupled with a tolerance. This height is determined as the athlete's standing erect. However, this may prove problematic in a combined classification of T43 and T44 athletes as the amount the prosthesis will compress by could be very different in uni-lateral athletes when compared to the biological limb. This could lead to greater asymmetry between their limbs or gait characteristics. Bi-lateral athletes will not have this issue as both limbs are artificial and an assumption is made that these would compress by the same amount on both sides.

3.8 CONCLUSION

Whilst the cases of controversy surrounding technology used in disability sport are few in number, those that do occur have the same issues as those in able-bodied sport. As a result, this coupled with evidence of ambiguity in the current rules would suggest an investigation into prosthetics technology is warranted.

To address such issues, ethical and philosophical discourse is more typically used as a means to resolve debate into whether a technology is used in sport or not. However, this is normally conducted retrospectively once the technology is already in service. The contested nature of philosophical debate would mean that use of this method alone is not enough to achieve the most robust and reliable attitude to managing technology's use in sport. However, the studies that use more quantifiable or measured data do not extend their findings to declare a clear position on such technology's inclusion.

As a result, a mixed method approach which uses the strengths and minimises the weaknesses of both quantitative and qualitative methods would be recommended to address the objectives of this thesis.

CHAPTER 4: RESEARCH METHODS

4.1 INTRODUCTION

Chapter 3 discussed how ethical and philosophical discourse is typically used as a means to resolve debate into the acceptability of technology within competitive sport. It was also reflected that the limitations of such approaches is that such methods can provide inconsistent, inconclusive or impractical findings. However, studies in the literature review that use a quantitative approach alone, have not offered any insight with respect to the sociological impact of performance inhibition or enhancement. It was therefore recommended that this research project would be best served by utilising techniques which have the strengths of both approaches to research method design. To reinforce this, the objectives of this research project are re-listed as follows:

- 1) To investigate the impact of any technological change of prostheses that has occurred in the sport and to ascertain whether any regulation on their acceptability would be of value in the future.
- 2) To investigate current perceptions of lower-limb running prosthesis used in competitive disability sport.
- 3) To develop guidelines for LLP technology inclusion when used in competitive running with a lower-limb amputation.
- 4) To investigate the assessment of lower-limb running prosthesis and to recommend appropriate testing strategies.

Objectives one and two refer to qualities such as ‘impact’ and ‘perceptions’ and are potentially qualitative in nature. These are balanced by objective three’s ‘guidelines’ and objective four which refers to recommending appropriate testing strategies. Whilst this could also be satisfied using qualitative research methods such as interviews, surveys or quantitative

alternatives, the diversity of the objectives lend themselves to considering the merits of any research method rather than rigidly determining between a qualitative or quantitative approach. This is especially important as this the context of this research problem was one of a practical application. As a result, a mixed method approach was proposed to satisfy the research objectives of this research project.

4.2 MIXED METHOD RESEARCH

4.2.1 Background

Mixed method research (MMR) is based upon the concept of *triangulation* – ‘a combination of methodologies in the study of the same phenomenon’ (Johnson et al. 2007). It has been defined as the application of different approaches when applied at any or all stages of a research project (Bazeley 2004) or single study (Driscoll et al. 2007). It has also been suggested as the logical alternative to the unproductive debate over the advantages or disadvantages of either qualitative or quantitative research methods (Feilzer 2010). It has become increasingly popular as the means to ‘combine elements from both qualitative and quantitative paradigms to produce converging findings’ (Lingard et al. 2008) and as the ability to provide much more comprehensive solutions that using either qualitative and quantitative methods alone. Mixed methods has been proposed as disseminating knowledge for practical use (Sale et al. 2002) or that today, its primary philosophical advantage is one of pragmatism (Feilzer 2010) and a high regard for reality (Johnson et al. 2007). As such, the advantages of MMR have been suggested as the ability to expand the scope of breadth of research by offsetting the weaknesses of either approach alone (Doyle et al. 2009; Driscoll et al. 2007) or by combining the strengths of both (Morgan 1998). It allows researchers to be more flexible and holistic in their investigative techniques (Onwuegbuzie & Leech 2004).

Ultimately, mixed method research has been proposed (after both qualitative and quantitative method research) as the third paradigm or methodological movement (Doyle et al. 2009, Johnson and Onwuegbuzie 2004).

MMR has also been referred to in name as *multi-method*, *integrated*, *hybrid* or *combined* research (Driscoll et al. 2007), *blended*, triangular studies (Johnson et al. 2007), *multi-strategy* (Bryman 2006), *mixed research* (Onwuegbuzie & Johnson, 2006) or *mixed model* (Tashkkori & Teddlie, 1998). The variation in the practises definition has been suggested that this is due to the impact of combining different techniques beyond that of just the initial data collection methods used (Tashkkori & Teddlie, 1998) and should refer more so as a research approach covering research methods, data analysis, procedures or inferences (Johnson et al. 2007).

4.2.2 The Nature of Mixed Method Research

The mixing of methods to resolve research questions can be a parallel or sequential use of different methods or that both are being fully integrated into a single analysis (Bazeley, 2004).

Whilst, the expression 'mixed methods' suggests a general approach, a developed five point model for mixed method research's rationale was summarised by Onwuegbuzie and Leech (2004) and Bryman (2006) as:

- *Triangulation* - seeking convergence and corroboration of findings from different methods that study the same phenomenon.
- *Complementarity* - seeking elaboration of one method with results from another.

- *Development* – using the findings from one method to help inform the other method.
- *Initiation* – discovering paradoxes and contradictions that lead to a reframing of the research question.
- *Expansion* – seeking to expand the breadth and range of inquiry by using different methods for different inquiry components.

Onwuegbuzie and Leech (2004) suggest that every MMR study would likely have one or more of these underlying purposes.

Further detail of MMR practise refers to how multiple research methods relate or are undertaken with respect to each other. These have been defined as *parallel mixed analysis*, *sequential mixed analysis* and *concurrent mixed analysis* (Onwuegbuzie & Leech 2004).

Parallel Mixed Analysis

The basic premise of parallel mixed analysis is that the multiple studies are conducted separately, that one does not influence the other and that the results of either are neither compared nor consolidated until both sets of data analyses have been completed (Onwuegbuzie & Leech 2004). They do require pre-planning of the separate strands of the research once the research objectives have been determined (Johnson & Onwuegbuzie 2004). An example of this, as defined by Driscoll et al. (2007) is shown in figure 13.

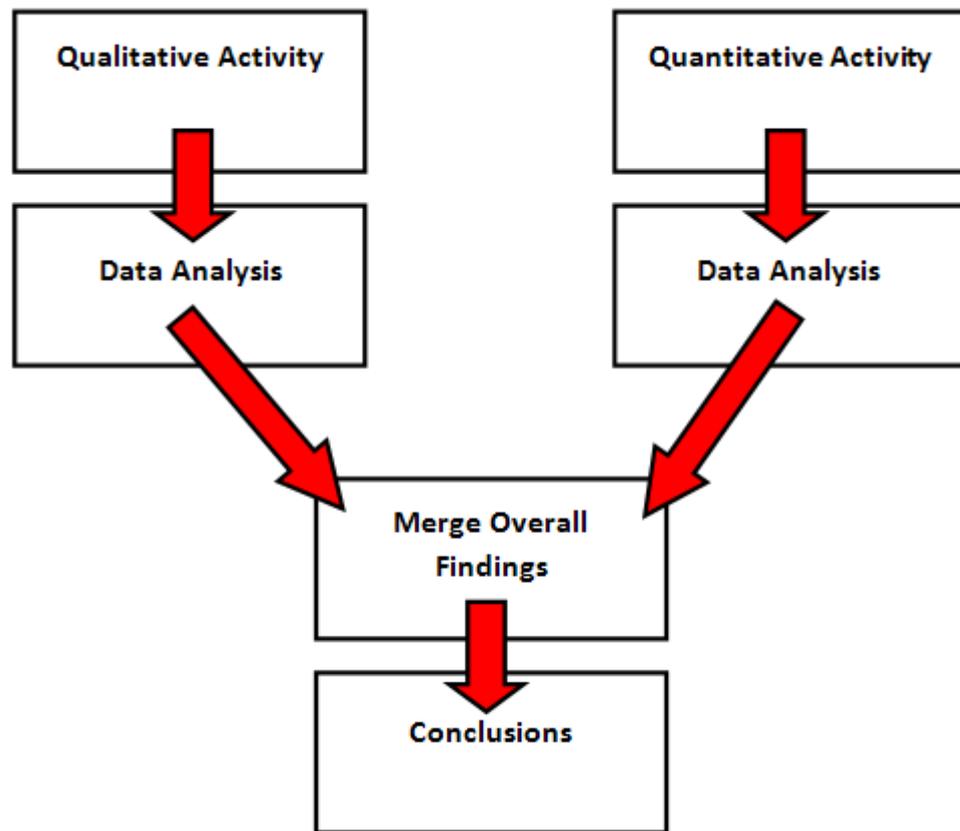


Figure 13. Parallel MMR

Sequential Mixed Analysis

With sequential mixed analysis, the multiple periods of data collection, analysis and inference are employed in a series of phases. In this case, data analysis will take place before all data for the research project is collected (Onwuegbuzie & Leech 2004). An example of this, as defined by Driscoll (et al. 2007) is shown in figure 14.

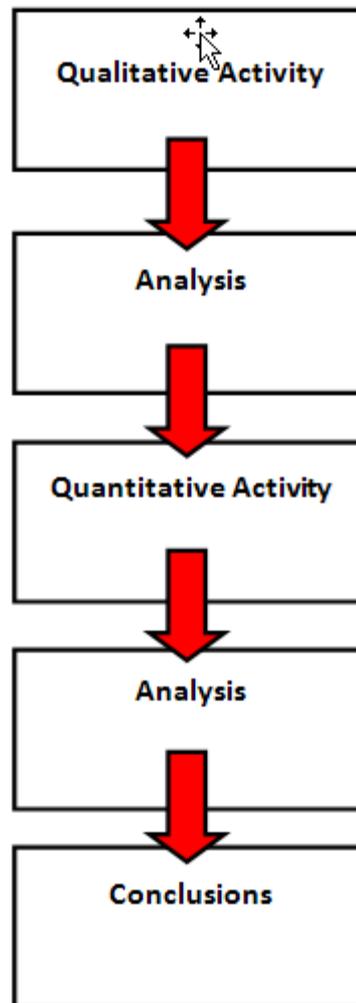


Figure 14. Sequential MMR

Concurrent Mixed Analysis

With concurrent mixed analysis, all the data is collected at the same time but unlike the parallel approach, integration takes place at the analysis stage not after these have been completed independently (Onwuegbuzie & Leech 2004). An example of this, as defined by Driscoll et al. (2007) is shown in figure 15.

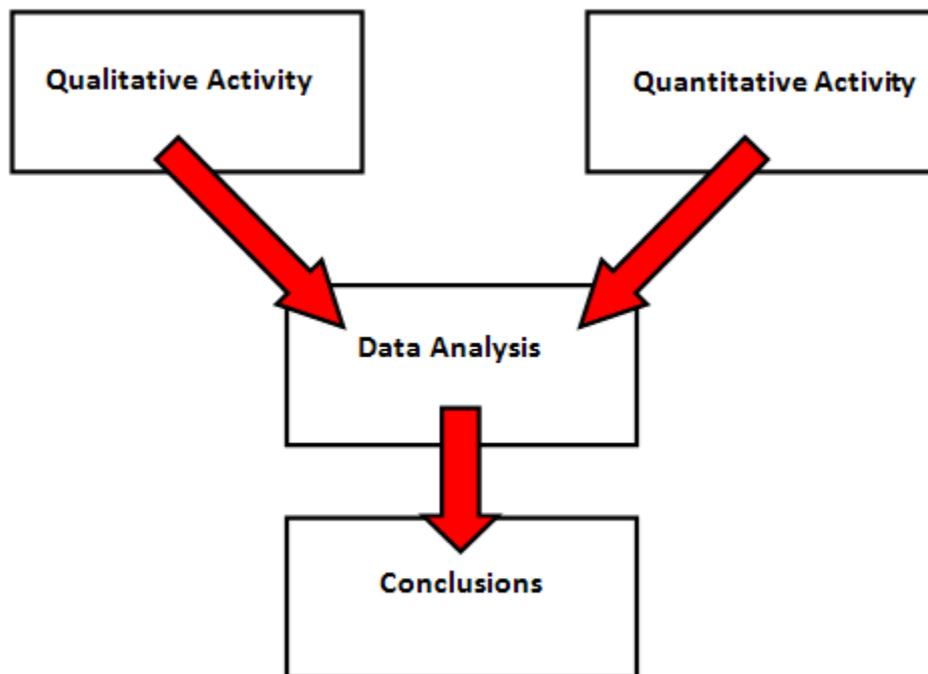


Figure 15. Concurrent MMR

The number and style of activities for the configurations in figures 13-15 are not rigid and may be unbalanced or non-symmetrical as research and expertise requires.

Whilst the different methods within MMR are generally defined, the rationale for choosing, sequential over concurrent mixed analysis is not clear. It is therefore assumed that this is left to the individual based on the specific characteristics of the research problem or using frameworks such as the five point guidance model outlined by Onwuegbuzie and Leech (2004) earlier. As such, the guidance is descriptive rather than prescriptive.

An alternative approach is to define the structure based upon the weighting of the qualitative research against of the quantitative portions. These have been defined in a model by Johnson et al. (2007) as:

- QUAL+ (qualitative research phases are dominant)
- QUAN+ (quantitative research phases are dominant)
- Equal Status (equal status of all phases)

4.2.3 Criticism of Mixed Method Research

The criticism surrounding MMR approaches is that the level of integration can vary in some cases so that the various qualitative and quantitative approaches are treated as separate domains rather than being woven together (Bryman 2007). This criticism has centred on how two sub-studies are directly related to each other and just how much integration between them is required (Tashakkori & Creswell 2007) or evident (Feilzer 2010). However, it is not clear whether this is actually a shortcoming of the technique or merely a characteristic of it. It is suggested that additional research in the area of MMR integration is required to clarify this further (Johnson et al. 2007). It is offered by Bryman (2007) that research may actually be informed differently and be of even greater value if the various strands of research activity are allowed to inform each other rather than remaining independent of each other.

It has been argued that by using MMR, the depth and flexibility of qualitative research is lost by then attempting to quantify it. It would seem that such concerns would be minimised or prevented, dependant on whether a researcher uses a parallel, sequential or concurrent method. In addition, the very advantage of MMR is that it provides findings that can be both practical and pragmatic (Johnson et al. 2007). As such, there would seem to be a trade off between a loss of quality vs an increase in practical application of research findings to researchers that would likely have to be weighed up on an individual case by case basis. Crucially, it is conceded that all research methods are superior to others under different circumstances (Johnson & Onwuegbuzie 2004).

Other criticisms of MMR are that researchers may naturally weight or favour methodological preferences over others in their findings (Bryman 2007; Johnson et al. 2007). However, this would be evident with any research method selection process, not just those using MMR approaches. In addition, they have been shown to write their findings for different audiences by unknowingly biasing one set of findings over another (Bryman 2007). The creation of models which acknowledge different balances attempts to counter some arguments over whether equal status is even realistically possible (Johnson et al. 2007) especially as this can produce contradictory findings or be reasonably assessed coherently (Morgan 1998). Any claims of bias would depend on the background of the researcher but also on the vehicle for the researchers findings – i.e. whether for a particular journal publication (Bazeley 2004). In which case, alternative writing styles could be mistaken for bias rather than as a fault of the MMR approach itself.

Finally, it is claimed that by using MMR, it can lead to research findings that have unanticipated outcomes (Bryman 2006). However, in this case of the objectives of this research project, insight is required therefore unanticipated findings are welcomed and not seen as a negative impact of the technique.

Ultimately, a researcher should identify whether their understanding has been improved by using an MMR approach (Feilzer 2010; Bryman 2007). If the answer is that it has not, then arguably an MMR approach has either not been of value or incorrectly selected.

MMR application has historically been used in health and healthcare related research (Ostlund et al. 2011; Palinkas et al. 2011; Doyle et al. 2009) and also to develop sports policy regarding elite athletes (De Bosscher et al. 2010). This makes its intent attractive for this research project.

4.2.4 The Application of Mixed Method Research in This Project

Using the five point model as suggested by Onwuegbuzie and Leech (2004), this project required *development*. The project worked from a position that it is not known what current perceptions of LLP in running exist. As a result, it was not clear what opinions existed first before any steps could be taken to create or disregard assessment strategies of such technology.

This project used a consensus based technique (Chapter 6) to identify the current perceptions of LLP's. This then expanded the project into using other methods to develop these findings. As a result, the project followed a hybrid *parallel* and *sequential* mixed analysis model. The research's emphasis on providing insight into a novel area required the consensus technique to provide the insight and a catalyst that subsequent quantitative approaches would then be used (either sequentially or in parallel) to provide the proposed findings and solution.

A graphical representation of this projects process is shown in figure 16.

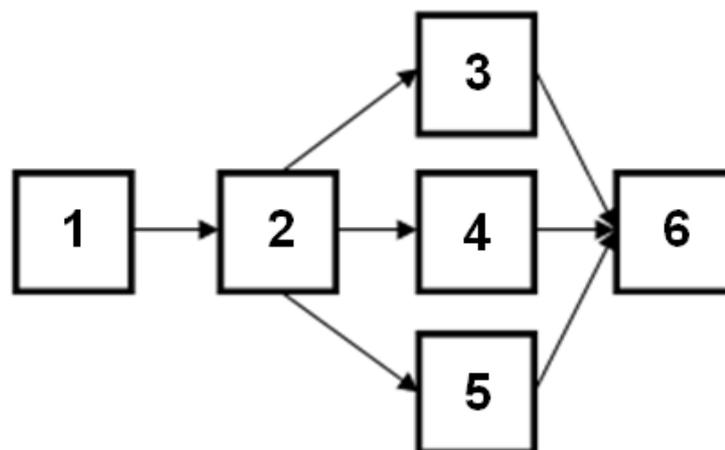


Figure 16. MMR Process

Phase 1,3,4,5 and 6 are qualitative driven studies. However, phase 2 is a consensus technique. Whilst consensus techniques have been defined as qualitative approach's (Williams & Webb 1994; Bowles 1999), these claims have been opposed by suggesting that they can generate both qualitative *and* quantitative data and should be considered an approach rather than categorised as a generalised research philosophy (Stewart, 2001).

Therefore, for reasons of clarity, phase two is not considered exclusively a qualitative study in this project, even if it uses such approaches in its data analysis. Ultimately, the mixed methods philosophy in this project is defined as a combination of different research approaches and analysis as expressed by Johnson et al. (2007) rather than whether the data collection was undertaken using qualitative or quantitative methods in isolation.

Since a sequential/parallel hybrid mixed method research strategy was employed, the specific research methods for each phase of this project will be addressed within their respective chapters of this thesis rather than this section.

**CHAPTER 5: THE IMPACT OF LOWER-LIMB
PROSTHESES TECHNOLOGY ON RUNNING
PERFORMANCE & PARTICIPATION (1976-2012)**

5.1 INTRODUCTION

Chapters 2 and 3 concluded that the understandings of ESR's function were still in a state of relative infancy. It was also discussed how controversy and issues surrounding sports technology inclusion and its ethics have taken place in both able-bodied and disability sport.

Disability sport is unique when considering sports technology inclusion in that it requires technology to help facilitate it (Burkett 2010). It has been suggested that artificial aids have no place in sport (Holowchak 2002) yet events like amputee sprinting or wheelchair racing would not be possible without assistive technology. Taking both of these views onboard, if prosthesis technology is purely to facilitate the ability to undertake disability sport, it should hypothetically be (philosophically speaking) *performance neutral*.

Whilst it is problematic to predict what technology may be introduced in the future, an evaluation of a major technological change in the past was investigated to identify what issues existed in competitive amputee running. ESR's have now been used in competitive racing since 1988 (Nolan 2008) but it was not known what impact such technology may have had when it was introduced. By investigating the known change in technology from non-ESR's to ESR's, such information would provide insight into the background of running prosthetic limbs and help the pursuit of any assessment strategies.

5.2 OBJECTIVES

The aim of this chapter is to investigate the introduction of ESR's into widespread use of the Paralympic Games competition in lower-limb amputee running. The objectives of this study are defined as:

- a) To identify if the performance of lower-limb amputees significantly changed over the assessed timeframe
- b) To identify if any performance increase by amputee runners were different to their able-bodied direct equivalent.
- c) To see if any changes in athlete performance are linked to participation levels.
- d) To propose if the 1988 anecdotal introduction of ERRP has any impact in the sport.
- e) To identify if any evidence exists for a model to define the acceptability of LLP's in amputee running.

5.3 METHODS

When considering historical data from 1976-2008, the only publically available and consistent data available was information regarding athlete *performance, athlete participation* and *medal allocations*. To determine ESR's impact and assessments of fairness, all of these were used to evaluate the proposed 1988 technological introduction of the ESR in the male 100m event. This event was the only one that can be selected as either the longer 200m and 400m distances or female athletes had not been run continuously or over the allotted timeframe.

Whilst it was stated in chapter 1 that the classification code has been changed several times since amputee racing's inception in 1976, all the codes comprising trans-tibial amputees from 1976-2012 were included in the study for analysis.

5.3.1 Performance Improvement

Performance data has been used as a means to imply some level of societal change in sports events (Balmer et al. 2011; Foster et al. 2010; Haake 2009; Munasinghe 2001). The limitations of relying on the most basic qualitative data is that such variation in sporting performance can only imply, not specifically identify the rationale for any change.

Whilst several mathematical methods have been used to model athlete performances (Watts et al. 2012; Foster et al. 2011; Munasinghe 2001), few have been proposed to investigate the specific impact of sports technology (Balmer et al. 2011; Haake 2009). The Balmer (et al. 2011) method uses double logistical growth as a means to determine the impact of technological innovation. However, the Haake (2009) method is more specific as it considers the actual physics that applies to a sport and then uses any significant changes in event specific physics to act as an indicator of technological impact. The Performance Improvement Index (PII) primarily assesses sports performance change from one date to another using the results of an event (Haake 2009). It ultimately identifies proportions that may be attributed to sports technology and provides a metric which forms a direct comparison to other sports that rely on different metrics (such as speed, distance, or time). The PII has also been used to explore the impact of World Wars 1 and 2 upon running short, middle and long distance world records (Foster et al. 2010), and on the impact of technological innovation in Olympic field jumping events (Balmer et al. 2011). The PII cannot currently identify the exact proportion of impact of sports technology change, but it has been shown to corroborate anecdotal evidence of change such as the inception of

new materials used for the pole vault or a change in the aerodynamic design of bicycles (Haake 2009). As a result, it is a complementary tool to inform debate rather than to generate substantive findings.

When considering timed events over fixed distances, Haake (2009) defines the Performance Improvement Index as:

$$Index = \left[\left(\frac{t_1}{t_2} \right)^2 - 1 \right] \times 100$$

This formula has been derived as part of a linear regression from a larger formula (Haake 2009). This formula addresses work done by a body overcoming aerodynamic drag when moving and for a fixed air density. It comprises a first timed perform t_1 divided by a second performance t_2 . The rest of the formula converts the change between two performances and expresses it as a percentage.

This formula assumes events requiring motion to be dominated by aerodynamics. However, it should be noted that air resistance increases exponentially as speed increases (Kyle 1991). The proportion attributed to the air resistance of a 100m sprinter running at 22.5mph is going to be proportionally less than a cyclist performing a 4Km individual pursuit at 31mph. As a result, the magnitude of the PII index may be skewed if comparing events that result in different absolute and average speeds.

To reinforce the PII, the second method will be the percentage increase of a performance from one Paralympics Games to the next. This is expressed as:

$$\left[\left(\frac{t_1}{t_2} \right) - t_1 \right] \times 100$$

Like the PII, t_1 is the first performance and t_2 the subsequent performance. The result of this change is also expressed as a percentage.

The mean average of the fastest 3 runners in each successive Paralympic Games were used as a basis for assessment. These fastest three athletes would be those who would 'podium' thereby winning bronze, silver or gold medals. By considering a mean of a group of runners rather than outright world records or event winners, outliers or generation defining athletes were reduced in impact which could skew any analysis. However, the full field of a final was not used as it was an issue that the early Paralympic Games saw incomplete 8 person finals and a relatively novice standard of competition. By limiting this sample to the medallists, it was felt that those that may have been merely attending and having not needed to formally qualify to be of a competitive standard (unlike able-bodied athletes at the Olympic Games) was felt would reduce skew in the data.

The results of amputee sprinting at the Paralympic Games were taken and compared to the nearest able-bodied equivalent, the *Olympic Games*. Both competitions take place every 4 years, are accessible by the same countries of athlete origin and since 1992 have taken place at the same venue using the same facilities.

Three 36 year data evaluations were compared:

- Amputee sprinting (AS): The change from Paralympic Games to Paralympic Games over the 1976-2012 time period.
- Able-bodied Modern Period (MP): The change from Olympic Games to Olympic Games over the 1976-2012 time period.
- Able-bodied Inception Period (IP): The change from Olympic Games to Olympic Games over the 1896-1932 time period.

The AS to the MP comparison provided information that shows the performance of athletes over the same time period. The AS to IP comparison

provided information that shows the impact of a new event developing at the highest elite level of competition. In the case of the able-bodied 100m sprint, this took place nearly 100 years prior to the Paralympic Games equivalent.

5.3.2 Participation Data

Athlete participation data was used to track trends to ascertain any level of change over the 32 year time periods. This interest was based on a previous study that has claimed technological change is more responsible for increases in performance than widening participation (Munasinghe 2001) and that increases in global population will not impact on athlete performances (Foster et al. 2010). This data was drawn from the classifications inception in 1976 up to the 2012 games. The athletes' total participation number and country of representation was recorded.

The data of both athlete performances and athlete participation have been taken from the official governing body's website (<http://www.paralympic.org/Athletes/Results>). This data is available within the public domain.

5.3.3 Medal Allocations

The results from 1976 to 2012 were assessed to determine which countries won gold, silver or bronze medals and how many athletes started each event at the Paralympic Games.

5.4 RESULTS

5.4.1 Performance Improvement of Amputee Sprinting

The data derived from the timed performance of lower-limb amputee sprinting from Paralympics to subsequent Paralympics over the 1976-2012 timeframe is shown in Table 5.

Table 5: Amputee Sprinting Improvements 1976-2008

Paralympic Games	Mean podium time (s)	Percentage improvement from prior games (%)	PII improvement from prior games (%)	PII improvement from 1976 baseline (%)
1976	14.40	n/a	n/a	n/a
1980	14.01	2.7	6	6
1984	13.62	2.8	6	12
1988	12.37	9.2	21	36
1992	12.19	1.5	3	40
1996	11.78	3.4	7	49
2000	11.40	3.2	7	60
2004	11.12	2.5	5	68
2008	11.29	-1.5	-3	63
2012	11.00	2.6	5	71

Note. PII = performance improvement index

It is evident that both the 'games to games' percentage increase and the PII demonstrates substantial improvement in 1988 with an increase well in excess of other AS 'games to games' scores. There is no evidence of change in PII in amputee sprinting either prior to or since 1988. Progress in improvements can be demonstrated until 2008 when performance times generally decrease.

5.4.2 Performance Improvement of Able-bodied 100m: IP

The data derived from the timed performance of able-bodied sprinting from their inception at the Olympics over the 1896-1932 timeframe is shown in Table 6.

Table 6: Inception Period Improvements 1896-1932

Olympic Games	Mean podium time (s)	Percentage improvement from prior games (%)	PII improvement from prior games (%)	PII improvement from 1896 baseline (%)
1896	12.27	n/a	n/a	0
1900	11.10	9.5	22	22
1904	11.13	-0.3	-1	21
1908	10.90	2.1	4	27
1912	10.87	0.3	1	27
1920	10.80	0.6	1	29
1924	10.70	0.9	2	31
1928	10.87	-1.6	-3	27
1932	10.42	4.29	9	39

Note. PII = performance improvement index

Able bodied sprinting from its Olympic Games inception saw progressively low rates of improvement. However, there was a spike, equal to that of the AS 1984-88 Paralympic sprinting improvement from 1896-1900. The reason for this (be it social, technological or other) is not known.

5.4.3 Performance Improvement of Able-bodied 100m: MP

The data derived from the timed performance of able-bodied sprinting from their inception at the Olympics over the 1976-2012 timeframe is shown in Table 7.

Table 7: Modern Period Improvements 1976-2012

Olympic Games	Mean podium time (s)	Percentage improvement from prior games (%)	PII improvement from prior games (%)	PII improvement from 1976 baseline (%)
1976	10.09	n/a	n/a	0
1980	10.31	-2.2	-4	-4
1984	10.13	1.7	3	-3
1988	9.96	1.7	4	3
1992	9.99	-0.3	-1	2
1996	9.88	1.1	2	4
2000	9.97	-0.9	-2	3
2004	9.86	1.1	2	5
2008	9.83	0.3	1	5
2012	9.72	1.1	2	8

Note. PII = performance improvement index

The general trend progressions of the mean podium of all three time periods in this study are compared in Figure 17.

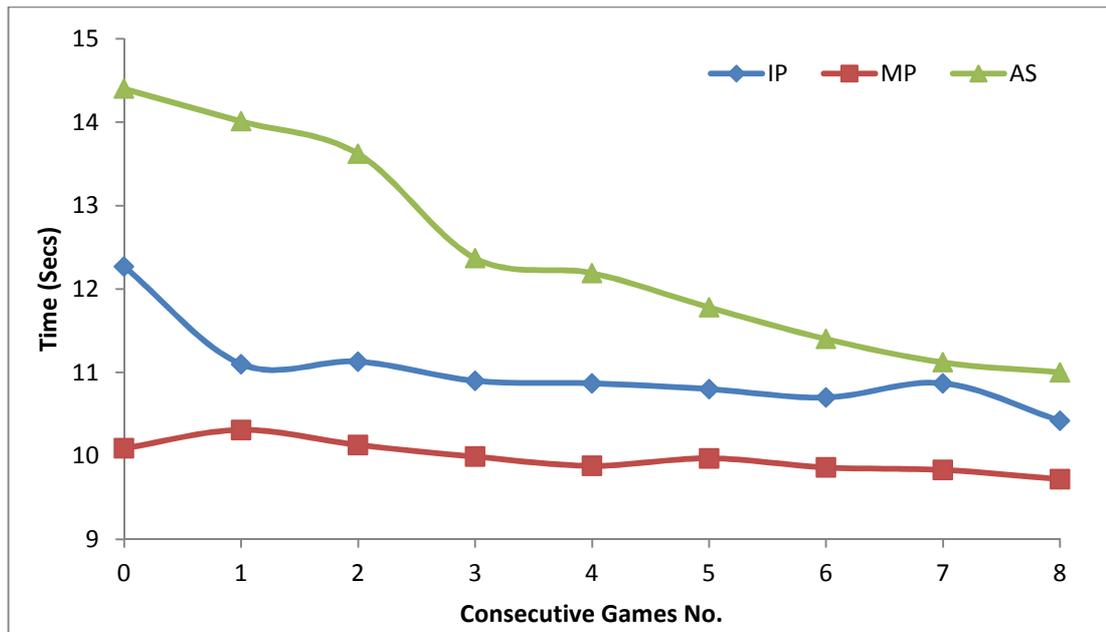


Figure 17. Performance Improvement Index of Timeframes

It can be seen that at the start of the evaluated time period, the three traces are wide apart. However, by the end of the 36 year duration they have narrowed significantly. Whilst the MP group has seen relatively little progression, the AS mean time has been subjected to a substantial reduction in the mean podium performance.

The 'games to games' PII changes of AS and able-bodied MP and IP over their 36 year periods can be compared together as shown in Figure 18.

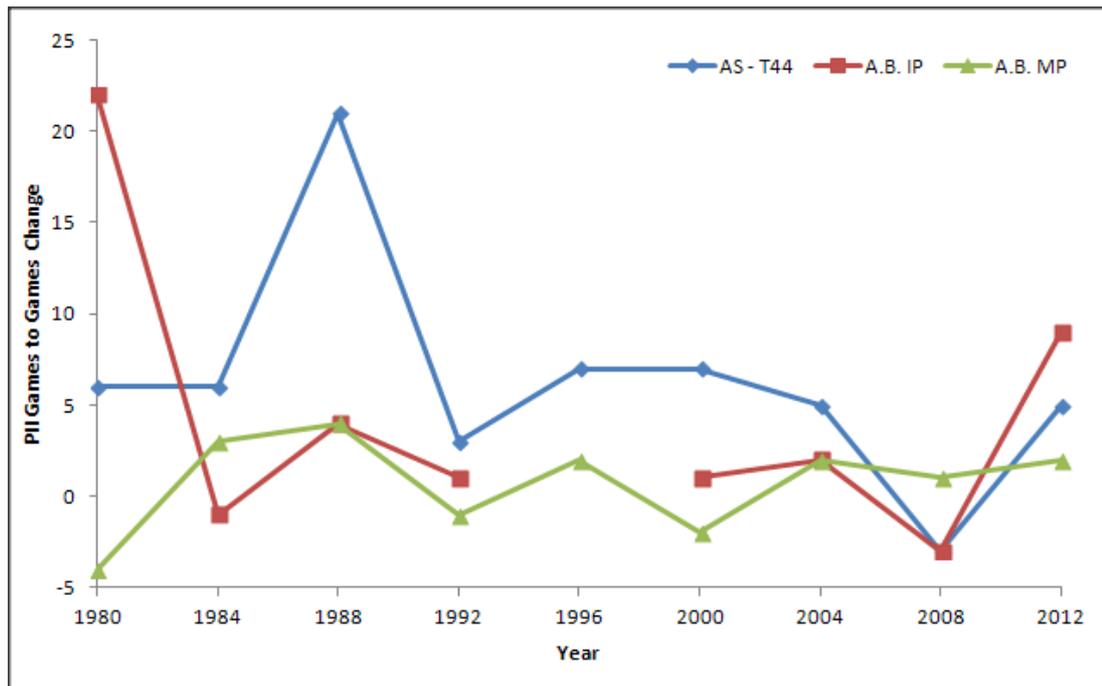


Figure 18. Performance Improvement Index of Timeframes

It should be noted that the gap in IP's trace was due to there being no Olympic Games held in 1916. The magnitude of the change in the AS (T44) event is shown by the steep peak in 1988 (games no.3). After this point, the AS rate reduces in magnitude until 2012. The IP timeframe also sees a slight increase at the end of its 30 year period despite relative stability prior to it. The MP period seemed to be in a state of relatively marginal improvement.

5.4.4 Participation Data

36 countries have sent athletes to the eight Paralympic Games held between 1976 and 2012. The total number of eligible race 'starts' by athletes was 159 (inclusive of those who did not finish).

Figure 19 illustrates the number of nations participating and the total number of athletes competing in the lower-limb amputee 100m sprint event at each games.

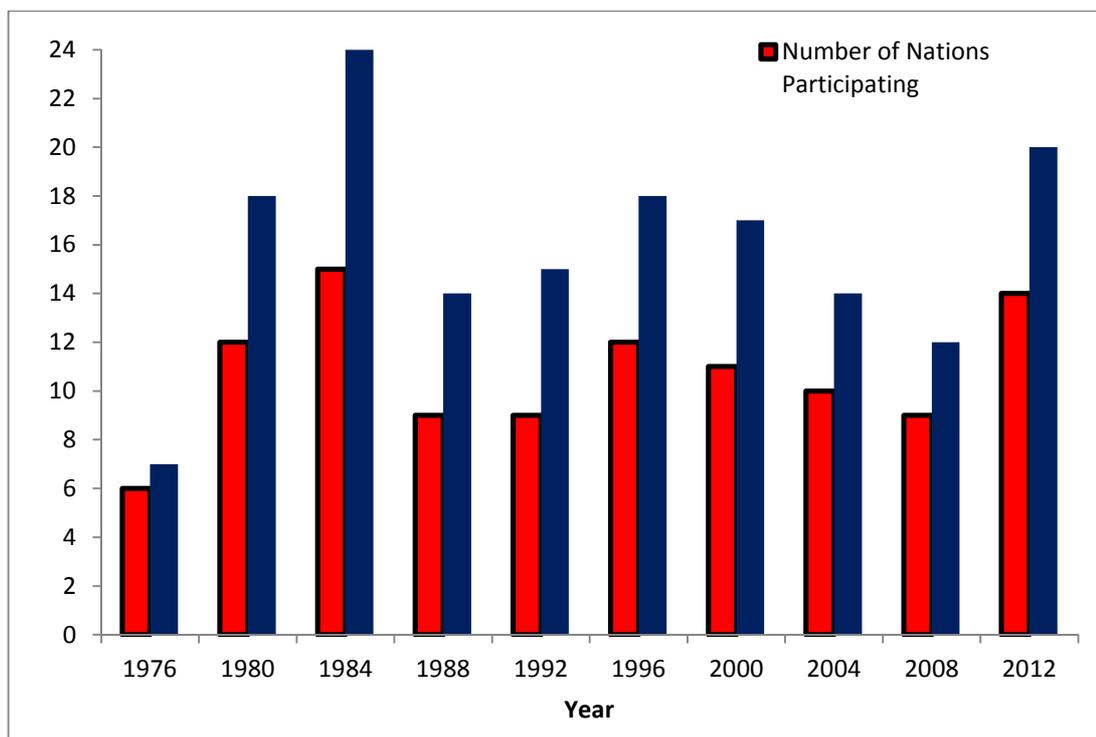


Figure 19. Amputee Sprinting Historical Participation Levels

It can be seen that the number of competing athletes peaked in 1984 with a sharp decline in 1988. There is a gradual second minor peak at the 1996 games and then a gentle decline until the biggest increase seen since 1984 in 2012. This trend is also reflected by the total number of countries sending athletes to compete in this event. It is unclear what may have caused a positive change in 2012 having suffered a gradual decline prior to it. It should be noted that (as mentioned in the introduction) the disability classifications were changed over this period. However, there was no such change between 1984 and 1988.

5.4.5 Medal Allocations

The total number of medals awarded from 1976 to 2012 was 30. The medal allocations and the number of athlete 'starts' are shown in Table 4. An athlete 'start' is an athlete who had been stated on the results sheet as having signed on for the event. Such athletes may have suffered a 'did not finish' classification (DNF) in some cases and therefore not recorded a result.

The data showed that the USA have the highest level of athlete 'starts' and are the most prolific medal winners taking most of the medals awarded over the ten games. Before 1988 the USA have a medal win ratio of 0, but this increases substantially to 0.61 from that point onwards. Australia had the second highest level of participation with 16 athlete 'starts' and a relatively balanced medal win ratio of 0.5 and 0.42, pre and post 1988 respectively. Germany (inclusive of West Germany's results pre 1992) and Canada had the next highest level of participation, but return low rates of medal tally. South Africa shows a high start/win ratio since 1988, but it should be noted that the majority of these wins were attributed to Oscar Pistorius who is actually a T43 athlete included within the T44 classification. All the other nations with early support of the event up until 1988 had failed to secure a medal or to participate since the 1988 games – notably Myanmar, Poland and Israel.

5.5 DISCUSSION

Able-bodied sprinting has generally shown consistent, yet marginal improvements in performance. Amputee sprinting on the other hand has not directly followed the trends of able-bodied sprinting, either with its original inception into the Olympic Games nor over the same timeframe from 1976-2012. A spike in 1988's amputee sprinting results was clearly identified whereas able bodied sprinting appeared much more stable. Whilst the PII value cannot specifically identify whether this is solely due to the known change in prosthetics technology, such information does corroborate the published introduction of ESR's (Nolan 2008). In addition, the magnitude of change is extremely large compared to any other Paralympic games to games increase over the evaluated period. This would suggest it is entirely plausible that the root cause is specifically related to changes in disability sports and technology. The rate of progression, whilst positive, has then generally decayed since 1988. An events decaying trend in performance

improvement has also been witnessed before in the able-bodied 100m world record (Foster et al. 2010).

It is shown that a PII of 21% occurred from 1984-1988. This is not as high as other values generated by Haake (2009) describing the changes in javelin technology, pole vault design or the cycling one hour event, but these were all over timeframes of at least 80 years. Considering that the maximum change in able-bodied sprinting would be 24% over a 100 year period (Haake 2009), the level of progression shown over a 4 year window could be regarded as somewhat unusual.

It is proposed that the spike seen in 1988 is attributed to the major revolution in the prosthetics technology as reported by Nolan (2008). It has been demonstrated that of a typical historical performance improvement change, some of this can be attributed to clothing (Haake 2009) or the social impact of war (Balmer et al. 2011), but the able-bodied athletes samples in this paper do not reflect any of the major spikes in PII that the T44 class had demonstrated. Acknowledging that there were no changes in disability classification at the Paralympics between 1984 and 1988 which could account for the sudden rise in performance, this suggests that there were other causative factors involved which are unique to disability sprinting.

Running performances themselves in the T44 event has continued to improve up until 2012. This demonstrated that medal winning performance had been unaffected with any issues relating to participation. However, it would be interesting to see in the future if the same applies to athletes who did not medal.

Increase in the cost or limited access to new prosthesis designs have been described as a basis of unfairness (Zettler 2009) and such issues have been

seen in other sports before such as with the introduction of clapskate speedskates (Van Hilvoorde et al. 2007). Unless new designs in lower-limb prosthetics are at least to the same level of access or cost as current ESR's, serious concerns are raised here to allowing them in the future. It is therefore proposed that the current level of technology is maintained until such time that newer prosthesis technologies are proactively reviewed before formal adoption to ensure that all competitors could reasonably afford and access it.

As for measuring success, many nations which won medals prior to 1988 ceased to do so after 1988. Nevertheless, excluding the 2008 games, the mean podium time of an athlete's performance has generally continued to improve. A large decrease in participation levels occurred for the 1988 games but did not drop substantially again until 1996. The analysis indicated that the introduction of the ESR may be the cause of the uncharacteristic rise in performance, overshadowing other more subtle potential improvements in athletes' achievements. It is proposed here that the excessive rate of progression from games to games compared to able-bodied competition had highlighted that the 100m T44 event has potentially been *re-skilled* through use of prosthesis technology. Re-skilling has been proposed as being used as a mechanism to consciously improve the game of tennis (Sheridan 2006). However, this explanation fails to take account of the magnitude of the technological intervention required to bring about this level of improvement. The participation data suggests it may have taken 24 years for the sport as a whole to recover from this.

The evidence presented here demonstrated a declining level of participation coupled with increasing levels of performance, even though overall athlete attendance at the games has been shown to continually increase (Legg & Steadward 2011). There are caveats to this proposal - it was not known what restrictions any nations might have applied to the number of athletes sent during this allotted time-period. The changes in participation levels could hypothetically be attributed to countries changing their attitude to athlete

selection. As a result, this warrants further investigation in the future. This said, a restricted athlete population in this class would seem unusual when it would require more than one nation simultaneously to be the cause. It would also seem unusual when it was considered that the overall Paralympic Games athlete population has steadily increased over this timeframe. It is worthwhile to find out why smaller nations such as Poland, Israel or Myanmar (who sent several athletes prior to 1988) suddenly failed to do so from this point onwards. It is possible that their athletes simply were not replaced when they retired, with younger ones of comparable standard but it would be a significant coincidence that several nations had this issue around the same time, who were all previously successful. The observations in this study do support Munasinghe's work (2001) that athletic performance is driven by changes in technology as opposed to just increases in globalisation.

In effect, if the LLP technology became less accessible (either in terms of cost or its supply chain) when prosthesis changed from 1988, then allowing such a change was ultimately an undesirable one.

It is also noted that the current T44 event was made up of both uni-lateral and bi-lateral amputees. Acknowledging that ESR's should likely remain in service for the foreseeable future, a review of how both types of amputee may have been advantaged or disadvantaged would seem to be of intrinsic value both to the athletes themselves and to the sport at large.

While the methods in this paper cannot conclusively point to the introduction of ESR's as being the root cause of change, their introduction at the same time as published improvements of such technology would seem to be a reasonable supposition. Considering that prostheses are proposed to be only restorative in nature (Burkett 2010), and demonstrating that the sports increases in performance to be excessive compared to able-bodied racing, it

was argued here that such change should have been investigated for its potential impact prior to its introduction.

This case study indicates several issues surrounding the value of technology in amputee running at the Paralympics. The increase in performances demonstrated that the prostheses used are either not 'performance neutral' or that alternatively, that they are still progressing towards a basic level of limb function restoration. What level of restoration required would require a baseline to be established. This study also raised indications that disability sport could also potentially be negatively affected by technology, echoing Tenner's 'revenge effects' (Tenner 1996) explained in chapter 3.

If another technological change was made within the sport but one that was not adopted by everyone (or took a period of time to do so), an underlying climate of fairness would be created. As a result, it is felt that the further development of a framework or model to determine the acceptability of prosthesis technology is warranted.

5.6 CONCLUSION

Amputee sprinting was evaluated over a 36 year period and compared to able-bodied sprinting over the same duration and time period to ascertain the impact of energy return prostheses. A major change in performance in 1988 was identified. However, it is proposed that such an introduction was excessive in impact when compared to the equivalent able-bodied racing. As an additional observation, participation levels have also not increased over this time period. As a result, it is proposed that the 1988 change was of little actual value to the sport as a whole in the short term. Whilst the innovation of energy return prostheses deliver proven health benefits to amputees in the general population, such technology should have been investigated for its potential impact prior to its introduction in elite disability sport. It is recommended for the foreseeable future, that the current appearance and basic spring-like function of prosthesis technology is maintained.

The issues caused by the introduction of ESR's in the case study demonstrate that the further development of a framework or model to determine the acceptability of prosthesis technology in the future is warranted. If any further technological change was made by an individual or a sport as a whole, a climate of technological unfairness would be created.

**CHAPTER 6: DEVELOPMENT OF A
FRAMEWORK FOR THE ACCEPTABILITY OF
LOWER-LIMB PROSTHETICS TECHNOLOGY IN
DISABILITY SPORT**

6.1 INTRODUCTION

Chapter 2 and 3's literature reviews demonstrated that several ethical issues surrounded the use of technology in sport generally and that this has also occurred when using disability technology in able-bodied sport.

New technologies open up new possibilities for better outcomes and processes as well as increased performance. The latter applies particularly to lower-limb running prostheses in disability sport. However, as for any new technology, there is the potential for unintended consequences and unforeseen implications for practice to arise as raised by Tenner (1996). As a result, the application of technological advances in the design of lower-limb running prostheses may threaten the integrity and fairness of the sport. Such issues were proposed as being apparent in chapter 4.

Chapter 3's literature review demonstrated that, despite well understood and common frameworks of philosophical criteria upon which to determine an appropriate outcome, such methods would often conflict or lack consensus. This conflict has been recommended to be overcome by means of obtaining consensus directed from a point of authority (Sakine & Hata 2004). It is important to find a direction informed by common values and shared notions of what is in the spirit of fairness in disability sport with a view to ensure a 'level playing field'. Thus a method was selected which allows the researcher to elicit and synthesize the opinion of people with specific experience and expertise as well as a stake in this area. Data obtained through such a method can generate informed perspectives on issues in relation to acceptability with the use of lower-limb running prostheses in disability sport.

The aim of the research in this chapter was to establish a consensus on the use of LLP used in running at the Paralympic Games and to better

understand the role and perception of such technology. From this information, proposed guidelines for defining LLP's use in disability sport will be made. This chapters study has seen peer review via journal publication (Dyer et al. 2011; Dyer et al. 2010) and is contained within Appendices F.

6.2 OBJECTIVES

The objectives of this chapter are:

- To determine what role running lower-limb running prostheses play within disability sport.
- To understand what (if any) limitations should be placed upon disability sport lower-limb running prostheses.
- To explore the perception of lower-limb running prostheses within an area of emerging interest.
- To create and to define a framework and/or guidelines for LLP acceptability in disability sport.

6.3 METHODS

A qualitative research strategy was deemed the most appropriate strategy in this Chapter. Such research does not necessarily require the inclusion of large sample groups which is important when considering that sport with a disability is performed by athletes in small numbers and has had a relatively short period of time to develop (as illustrated in Chapter 5). As a result, qualitative methods were selected as the more effective strategy at this stage of the mixed-method research process.

Due to the sensitive nature of disability, the research method selected should allow the generation of knowledge or opinion without the implications of intimidation, coercion or bias. As a result, research which provides anonymity was deemed desirable before selecting which method would be used to obtain this information. From this, whilst methods such interviews (both structured and semi-structured) would be an applicable method, this technique throws the proposal of any framework solely onto the researcher. However, it was felt that methods which allowed stakeholders to evaluate and refine any proposals using their own expertise would provide more pragmatic and realistic solutions to the research objectives.

The method selected to obtain the perspectives of a number of different groups and stakeholders and experts is a consensus based methodology and referred to as the *Delphi Technique* and is widely used in *inter alia* information and communication research, education, health and social care, and management studies. It seeks to elicit *expert* (Sackman 1975; Martino 1983), *peer* (Thompson et al. 2004) or *informed individuals* (McKenna 1994) opinion in a systematic manner. It is used to assist with decision making and can also be applied when there is incomplete knowledge about a problem or phenomenon (Skulmoski et al. 2007). It has also been employed whereby answers are vague, or subject to many interpretations (Chang & Kim 2003) or as a way to determine priorities and alternative futures (Beech 1999). These applications are particularly relevant as chapters 2 and 3 concluded that some of these principles are required to ascertain the acceptable use of prostheses technology for competitive purposes.

The Delphi method is a group technique with the aim to obtain the most reliable consensus of views of a group of purposively selected key informants, stakeholders or experts by means of a series of questionnaires which become progressively more focused. The process also involves controlled feedback to the respondents whilst maintaining their anonymity (Gupta & Clarke 1996; Kennedy 2003). The technique was originally

developed at the Rand Corporation in 1948 (Sackman 1975) and is named in deference to the legend of the Greek Oracle at the Temple of Delphi. The iterative process involves a series of 'rounds' of questioning to the same panel. The subsequent findings from each previous round are then communicated back to the respondents and the scope for variation reduced in the next round in order to achieve convergence of opinion (Sackman 1975). The purpose of the technique is to produce consensus among a group of informed individuals using flexible methods, reiteration and statistical results. It is not a method of discovery, but a way of accessing prevailing perspectives, values and opinions which is particularly appropriate in this context which is characterised by rapid change and still relatively unstable knowledge structures. The classic text by Linstone and Turoff (1975) includes a fuller explanation of this method. Whilst both interviews and focus groups could also be used to achieve the same objectives, the Delphi process has its unique advantages of its anonymity coupled with an ability to still achieve consensus on the issues at question.

The Delphi Technique has not been identified in published research having been applied to issues surrounding sports technology. However, it has been used to ascertain general priorities in disability sport (Wilhite et al. 2004), issues of health (Beech 1999), surgical intervention (Baumann et al. 2001), creating ethical frameworks (Winstanley & Stuart-Smith 1996) and in new and not fully understood technology (Sackman 1975). All of these applications of the technique are related in one aspect or another to the research aims in this chapter.

In the case of this study, three rounds took place involving electronic mail submission. The Delphi questionnaire design was not pilot tested due to the relatively small panel size and limitations of panelist availability typical within this context of study (Skulmoski et al. 2007). However, the questionnaire design was assessed by academic peers for suitable refinement and/or feedback. The Delphi process ran for three rounds, but also included some

additional e-mail contact during this process to some of the respondents when further clarification of their answers was required. The response rate of the Delphi process was high. This rate was 100% from the initial contact e-mail through to round one, 90% from round one to round two, and 100% from round two to round three. The duration of the study was approximately 6 months from initial agreement of participation of the respondents to the end of round three (inclusive of analysis).

6.3.1 Expert Panel Selection

The key principle of the Delphi technique is the recruitment and composition of an expert panel. The literature on the Delphi technique does not recommend one particular method to determine a credible number or type of 'expert' used as this will depend on the topic under investigation and the context in which it is being undertaken. For doctoral studies for example, expert panel size has varied from 8-345 participants (Skulmoski et al. 2007). As Bowles (1999) indicated, 'Expertise is a valid construct but it is not easy to identify who possesses it'. This opinion is echoed by Sackman (1975) in that definition or allocation of the term 'expert' is highly problematic but only strengthens the need to select a panel extremely carefully. A review of postgraduate use of the technique has shown most panel sizes being 5-20 participants in number. In its use as a forecasting tool, a typical range of 4-20 experts have been used with occasional occurrences with panels as big as 98 (Rowe & Wright 1999).

The experts for this study were selected through purposive sampling on the basis of their involvement with disability sports. Institutional ethical approval was obtained for the study before any contact of the respondents took place. The relationships between all stakeholders in disability sport were initially mapped graphically taken from the perspective of an athlete being at the hub and other areas of expertise connected to them. Anonymity of the panelists' identity and responses to each other is paramount to the Delphi technique. Without compromising participants identities, the final panel selected for this

research project included a number of lower-limb disability athletes (both active and retired), prosthetists (with experience of working with elite athletes), coaches, academics from a variety of related disability disciplines (ethics, physiology, sociology, philosophy, and biomechanics) and spectators of disability sport (who have witnessed disability running). The composition of the panel is shown in table 8.

Table 8. Delphi Panel

Panel Member Type	No.
Prosthetist	3
Disability Sport Academic	8
Disability Sport Athlete	4
Disability Sport Governing Body Member	1
Disability Sport Spectator	5

All expert panelists had direct experience of disability sport either through participation with or by academic publication within. Other than this primary engagement, an exact amount of the expertise experience was not specified. Once the stakeholders making up the potential panel were identified, all of the targeted panelists were contacted and invited to take part by e-mail prior to the formal start of the Delphi process. In total 21 experts were selected for the panel.

6.3.2 Definition of Consensus

The notion of consensus is difficult to define and thus problematic. Published research practice in the area suggests that the Delphi process continues through a number of rounds until a level of consensus is reached. It has been suggested that this is set prior to the study being undertaken (Fink et al. 1984). However, there is a range of percentage levels of agreement that are defined as consensus from 70% in some research (Hasson 2000) or

80% (Finger et al. 2006). Many published accounts do not set a pre-defined consensus level, merely stating the final percentage of agreement achieved (Abernethy et al. 2003; Thompson et al. 2004). It has been reported that some have taken consensus as low as 55% or as high as 100% 'leaving it up to the reader to determine whether consensus has been determined' (Powell 2003). A two-thirds majority was used for this study. This figure requires twice the level of positive agreement than for the views opposing it. This figure has been recommended a suitable level for defining consensus (Fink et al. 1984) and has been used successfully in health related studies (Barton 2009).

For the present study, two key conditions were put in place to act as definitions of consensus:

- i) A two thirds majority is obtained from a line of questioning (66.6%).
- ii) That the panelists failed to change their opinions on two consecutive rounds.

These conditions were defined in concordance with common principles which emerged as the literature of the Delphi technique was reviewed.

6.3.3 Round 1

The questionnaires (Appendices A.1) were sent as the main page of an individual e-mail to each panelist. The questions were preceded by a short introduction explaining the stage of the process. It was made clear that the process would involve subsequent rounds.

Round one asked three open ended questions based on the core aims of the study. It was to seek the expert's views on:

- i) What role they felt a lower-limb sports prostheses played in the context of competitive running.
- ii) What they saw as fair or unfair when using a sports prostheses.

- iii) What limitations they felt should or should not exist on such technology.

All three questions contained phrases such as 'in your view', 'if you can', or 'in your opinion' in order to invite and encourage respondents' personal views (grounded in their expertise) of the issues being investigated. This personal view is integral to the Delphi technique (Rowe & Wright 1999).

On completion of round one which achieved a 100% response rate the data was analysed and 17 themes (Appendices A.2) were identified through a process of *open coding*.

Coding is defined as an analytic process whereby qualitative data is categorised and named into cohesive themes (Moghaddam 2006; Ryan & Bernard 2003), whereby it is fractured, conceptualised and integrated to form theory (Strauss & Corbin 1998) or generate categories for integrating into a theory (Glaser 1978). Typically, coding was described by Strauss and Corbin (1990) with three basic styles. These are *open*, *axial* and *selective* coding. Open coding typically takes place at the beginning of a study and involves looking for emerging patterns and common themes (Moghaddam 2006). A theme is identified either through common typology, categories, metaphors, similarities and differences or merely through raw repetition in the transcribed text (Ryan & Bernard 2003). Both axial and selective coding refer to methods of formulating linkages and structure to the themes typically identified during after the open coding phase (Hoepfl 1997). However, since the Delphi round to round process through using an expert panel is intended to do this anyway (through the advantages of its very nature), those methods were not actively pursued in this study.

The limitations of the open coding process is that it has no preconceived process to follow (Walker & Myrick 2006) so there is a risk of bias (Moghaddam 2006) or varied interpretation (Kendall 1999) imposed by the researcher. However, this is a risk using many techniques of qualitative analysis. However, any bias can be reduced when using the Delphi technique as it uses the panel to form consensus and conclusions rather than the researcher.

Round 1's data was ultimately developed into a set of 12 closed questions for inclusion in round two with the aim of gaining consensus.

6.3.4 Rounds 2-3

Round two's closed ended questions used a 4 point modified Likert scale (Appendices A.3). This method was designed as a scale for assessing the respondent's attitudes (Clason & Dormody 1994). The intervals between each category cannot be considered equally when using ordinal data (Jamieson 2004) and as a result the mode was used to determine consensus. A neutral fifth choice was deliberately omitted in order to direct respondents towards a clear opinionated decision. A comments box was provided to allow the respondent to elaborate if they felt uncomfortable with this option.

A horizontal structure was used for the scale which provides a balanced visual layout between the views but also saves space within the questionnaire e-mail meaning the respondents would not have to scroll down great distances to complete it. An example of the round two question layout is shown in Figure 20.

No.	Statement		
2	The ongoing development of lower-limb running prostheses is part of the character of disability running competition.		
Strongly Disagree	Disagree	Agree	Strongly Agree

Figure 20: Delphi study round two question layout

The terminology used in the round two comprised the options ‘strongly agree’, ‘agree’, ‘disagree’ and ‘strongly disagree’.

As a result of round two, several of the themes were removed from subsequent rounds as consensus had already been obtained. This process kept the following rounds e-mails as short (and therefore as quick to complete) as possible.

Three themes based upon 5 questions did not obtain suitable consensus in round two. These questions were then reformulated on the basis of the qualitative feedback obtained in the previous round. The percentages of round two’s consensus were given to the panel for round three.

It became apparent upon review of round two that although there were 4 Likert options, respondents generally only used the middle two choices (agree/disagree) upon which to make their decisions. No questions had a mode average located within the ‘strongly disagree’ or ‘strongly agree’ options. As a result, it was decided that consensus would then be obtained by adding both the ‘strongly agree’ and ‘agree’ options together and likewise for the ‘disagree’ and ‘strongly disagree’ options. Ultimately round three moved to a two point Likert scale of ‘agree’ and ‘disagree’ with the comments box maintained but using the same, familiar layout and method as in round

two (Appendices A.5). An example of a round 3 layout is shown in Figure 21.

No.	Statement		
1	The lower-limb running prosthesis is a piece of sports <u>equipment</u> .		
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%; text-align: center; padding: 5px;">Disagree</td> <td style="width: 50%; text-align: center; padding: 5px;">Agree</td> </tr> </table>		Disagree	Agree
Disagree	Agree		
<i>Note to respondent: In the last round of questions, 63% of respondents agreed with this.</i>			

Figure 21. Delphi study round three question layout

Three questions were posed within the third round of the Delphi. All of these obtained the suitable consensus conditions as defined within this study. The respondents who had not agreed were contacted to see why they would not be willing to change their view. A fourth round was not deemed necessary as the consensus percentage obtained by this point then fell into the parameters set at the beginning of the study.

6.4 RESULTS

Round 1 of the Delphi involved a qualitative coding analysis. From the open coding process, 17 common themes were identified. These are shown in Table 9.

Table 9: Summary of Delphi Round 1 Themes

The role of the prostheses in disability sport
What the utilisation of a sports lower-limb prostheses provides to its user?
Is the prostheses part of the user?
Is it restorative or enhancement based prostheses technology?
What does a prostheses do ? (it's specific performance)
Is the user an athlete?, Which environment is it used in?
What external effect is caused through use of a sports lower-limb prostheses?
Issues relating to equity of access to prostheses technology.
Issue relating to the cost of prostheses technology.
Issues relating to mixed disability participation within a classification.
The use of passive or active technology in lower-limb prostheses design.
Issues relating to the ethos of Paralympic competition.
Issues relating to prosthetic limb length manipulation.
Recognising that a performance contribution exists through use of lower-limb prosthesis.
The physical effect of using a prosthesis.
The Delphi respondents' opinion to potential solutions at this stage.
Issues relating to prostheses stride length.

The themes identified in Table 8 each then had a question(s) developed to determine the actual opinionated stance of the expert panelists in these areas. Each theme provided the basis for a question that was developed for the following round in order to elicit panelists' responses.

Of the 12 close ended questions in round two, consensus of greater than 66.6% was obtained in 7 of the questions/statements (Appendices A.4). These are shown in Table 10.

Table 10: Delphi Round 2 Areas of Consensus

Delphi round 2 theme/statement/question	Level of consensus	Stance
The users of sports lower-limb prosthesis can be classified as 'athletes' as a definition	90%	Agree
The ongoing development of lower-limb running prostheses is considered part of the character of disability running competition	79%	Agree
The lower-limb running prosthesis is for restoring the physical ability of the missing leg to the athlete	79%	Agree
The lower-limb running prosthesis is to restore the functional ability of the missing leg to the athlete	89%	Agree
The lower-limb running prosthesis performance needs to have some form of control	83%	Agree
The lower-limb running prostheses maximum leg length should be restricted	74%	Agree
The lower-limb running prostheses should not provide a stride length beyond that of the users' current naturally determined level	83%	Agree

Five additional areas failed to gain enough consensus so these were further pursued into round three by question reformulation which were based upon the three themes from round 1.

The questions were refined based on both the comments and closed answers of round two. In addition, any terms that were seen to have assisted in obtaining consensus in round two were now integrated into round three's

questions. An example of this is use of the word ‘athlete’. The conclusions of round three are shown in Table 11.

Table 11: Delphi Round 3 Areas of Consensus

Delphi round 3 theme/statement/question	Level of consensus	Stance
The lower-limb prosthesis is a piece of running equipment	70%	Agree
In the case of an athlete with a single leg amputation, it is acceptable for a lower-limb running prosthesis to outperform their natural leg	70%	Agree
As long as it is within the rules of a sport, athletes with a lower-limb disability have the right to choose what technology they feel is appropriate to use	85%	Agree

Consensus on the issue of whether the lower-limb running prostheses was considered equipment increased from 63% at round 2 to 70% at round three.

The theme relating to the issue of a prosthesis being restorative in nature saw the consensus increase from 53% in round two to 70% in round three. This line of investigation saw some refinement in its question design with the addition in round three of a specific context.

6.5 DISCUSSION

The findings from the Delphi technique point to a number of common concerns among stakeholders related to use of lower-limb running prostheses in competitive disability sport which can be grouped around two themes:

- the nature of the function of lower-limb prostheses technology
- the nature of acceptability in relation to lower-limb prostheses technology

Following the second round of the Delphi study, agreement was reached in that a prostheses limb length and stride length should be measured against what would be achieved naturally if the athlete were not disabled and that critically prosthetic technology should be *restorative* in nature. Of course, this agreement is one of principle insofar as it would be problematic to ascertain what performance athletes with a unilateral amputation would have been capable of had they not been disabled, and virtually impossible in congenital bilateral amputees. In the case of unilateral amputees, a potential solution is to use their human limb as a datum of attainable performance for the prosthetic leg. This was supported after round two when it was agreed that a prostheses performance needs to be controlled and that the prosthetic technology should be limited to restoring both the function and the ability of the athlete. In summary, the prosthetic leg should not be able to outperform the sound limb. This does not clarify whether such technology should continue to be passive in nature although if it were not, could create short term adoption issues such as those illustrated in Chapter 5.

Related to the notion of prostheses being of restorative nature was the issue of whether prostheses were considered to be part of the athlete's body or as a form of 'equipment' and thus purely functional. Agreement on the latter view was achieved in the third round. Respondents were reluctant to agree

on the use of any type of technology being employed to restore function without knowing what that technology specifically involved. This was despite having already agreed that any prosthetic product used in competition had a defined limit to its performance. Such reluctance is probably due to an individual's decision on acceptability only being achievable when in full knowledge of the factors that have an impact on athletes' performances.

Additional concerns from the panel also related to both the *cost* and *access* to running ESR technology. The problem is that these are not realistically controllable on an international basis. Practically speaking, the variety of countries economical strengths (as well as the variability of a prosthetics manufacturers supply chain) would mean this would not be feasible unless the method by which equipment is currently provided is focused and controlled. The highly skilled nature of prosthetists and their availability would cause problems to athletes in developing nations if product distribution was affected. This approach however is not uncommon as one-design sailing dinghies such as the Laser Class have a focused, sole supplier to their World Championship and Olympic Games regattas. It is noted that both of these concerns were also detected in the general literature review in chapter 3.

Broadly speaking, agreement was obtained that in competitive disability sport, in order to measure, compare and rank competitors according to performance in a meaningful way, there is a need for equality of opportunities. This resonates with Loland's argument in relation to the role of technology in sport in that every competitor must be given equal access to resources such as equipment and equal opportunity to perform through a process of standardisation, specification and regulation of such equipment (Loland 2002). Such specifications will necessarily be related to what constitutes fair contests. Similarly, the findings of this Delphi study suggest that the prostheses development and use is considered part of the sport. It follows that the disability running legislation needs to reflect the attention to equipment similar to sports that have a similar human interactivity and

technological input (such as cycling). The stakeholders identified within round one that an enhancement based technology could be seen as unfair in several ways. Furthermore, agreement was eventually reached on the need for some form of limitation being placed on prosthetic technology. It is likely that this view is shared more widely among other stakeholders who suggest the need for an evaluation and clarification of the rules in order to ensure that it does not present unnecessary risks for harm, is acceptable and is of constitutive function and value in sport (Loland 2002).

6.5.1 Proposal of LLP Acceptability Guidelines

It was discussed in chapter 3 that the existing models of sports technology acceptability are too generic to be applicable in this context. In addition, it is not known if the more generalised ethical criteria used as basis for argument (summarised in table 3, chapter 3) were applicable in this context. The objectives of this chapter are used to develop a series of context specific guidelines for the use of LLP technology in disability sport. The objectives of this chapter were:

- *To determine what role running lower-limb running prostheses play within disability sport.*
- *To understand what (if any) limitations should be placed upon disability sport lower-limb running prostheses.*

It is argued that these have been resolved in the findings of this study by being designated as requiring to be regulated and being 'designated as equipment'.

The other objectives of this chapter were:

- *To explore the perception of lower-limb running prostheses within an area of emerging interest.*

This was resolved in the findings that the perceptions of LLP's are determined as a form of equipment and do not serve as an extension of the human body. It was also identified that the nature of this technology is that they are purely restorative both in terms of function and limb lengths (stride and general limb length).

The remaining objective in this chapter is :

- *To create and to define a framework and/or guidelines, specific in the context of lower-limb prosthesis acceptability in disability sport.*

All the findings in this study will be summarised into guidelines for LLP acceptability to satisfy this final objective. In addition, one of the key findings of chapter 4 recommended that any new technology should be reviewed prior to approval for racing as opposed to retrospective evaluation. This finding will also be incorporated into the guidelines.

The findings from chapter's 4 and 5 are amalgamated together to form the proposed guidelines. These are shown in table 12.

Table 12. Proposed Summary of LLP Acceptability Criteria

1	Lower-limb prosthesis used for competitive running are classed as equipment and will be formally legislated
2	Prosthetics technology not formally approved by the IPC should be submitted for evaluation to them ahead of any use of such designs in competition.
3	Lower-limb running prosthesis are restorative in nature.
4	Lower-limb running prosthesis will restore functionality to the user of no greater magnitude than that exhibited by the athlete's biological lower-limb.
5	Lower-limb running prosthesis will contribute to a limb and stride length of no greater magnitude than that exhibited by the athlete's biological lower-limb.

Point 1, 2 and 3 define the core philosophy behind LLP's use in disability sport. Point 2 will not fully resolve any revenue effects but will at least facilitate discussion. This may lead to further investigations using techniques such as those in this chapter.

Points 4 and 5 define LLP's intended performance. These points are problematic as they do not resolve the participation of bi-lateral amputees. It is argued that the use of a combined classification needs to be investigated further.

Point 4 and 5 defines that a threshold of lower limb function is an outcome measure but it needs to be investigated what (if any) tolerances should be applied to such recommendations. It is conceded that this study proposed in the discussion section that the athlete with a uni-lateral amputation biological lower-limb may have been functionally superior had he not been an amputee. However, this hypothesis is beyond the scope of this study and it is

felt that the remaining biological lower-limb is an objective governor for the performance of the artificial limb.

It is argued that point 5 (whilst a concern of the stakeholders in this study) is already dealt with via the IPC's legislation for calculating appropriate prosthetic limb length. As such, it is felt it should be included in these proposed guidelines. However, the literature reviewed in Chapters 1, 2 and 3 have shown that such behaviours have not been assessed under race conditions. It was also raised in Chapter 2's literature review of the potential importance of lower-limb to limb symmetry. As such, it is felt that such concerns over limb length manipulation should be investigated further.

6.6 LIMITATIONS

The Delphi process did have some limitations. The results generated are a 'moment in time' evaluation (Kennedy 2003). This means that any decisions based on the findings of this study have a timeframe of credibility before the exercise should be repeated. However, this would be evident with any legislative proposals or changes within governance.

Criticism of the Delphi technique has suggested a lack of credible validity and reliability and lacks professional standards (Sackman 1975). However, the very ethos behind the Delphi technique is to solicit *expert opinion* rather than empirical reliability (Martino, 1983). This means the exercise is only as good as the expert panel selected (Armstrong 2001; Gupta & Clarke 1996). The expertise evident within the panel in this study was extremely diverse from a wide range of stakeholder interests.

Sackman (1975) also suggests that the Delphi technique creates a 'forced consensus' or a watering down of opinion yet this would be evident with many survey techniques used across a broad spectrum of respondent demographics (Kennedy 2003). In addition, the breadth of an individual's opinion could mean that this problem would never be attempted to be resolved unless a consensus could be obtained. This is what this very study provided.

Round 1 of this study also raised the theme of whether the prosthesis should remain passive or not but it was felt after the Delphi study was concluded that this was not sufficiently followed up on. Chapter 5 proposed that the current level of technology should be maintained in the short term. Chapter 6's study does define the maximum threshold of performance as 'restorative' but did not address whether the sports technology could move beyond passivity as the minimum threshold.

Some refinement of the questions took place between all three rounds. It could be argued that such a refinement means any shift in consensus is not a true reflection of a change in opinion. However in this case, this allowed the panel to help refine as well as respond to themes and questions. This not only enriched the process but reinforces the very nature of the Delphi technique.

6.7 RECOMMENDATIONS

The aim of this study was to provide a set of shared views and values in relation to the role of technology in disability sport in particular based on the agreement achieved by a panel of stakeholders. The information supports the need for increased regulation of lower-limb running prosthesis technology. The values defined by this study will serve as an ethical

foundation (Freeman 1991) upon which any assessment strategy could be based. This research could be enhanced further by conducting a similar process periodically to help approve or refine proposed assessment strategies.

The proposed guidelines in section 5.5.1 require further clarification. The definition of 'functionality' of the lower-limb is not clear and is ambiguous at this time. Such ambiguity should be resolved by determining context specific assessments with respect to this thesis' research aims and objectives. Despite proposing the need to regulate such technology, it is not yet clear whether the prosthesis would be attached to the user or not when assessed (or both). The suggestion in this study is that by being equipment, the prosthesis would be independent. As a result, with current levels of technology, only mechanical properties could be assessed due to ESR's passive nature. This may not be applicable in this context so such methods should be investigated further.

Whilst these guidelines have attempted to define what is fair, acceptable and considered a natural limit to such technology, it is not known how bi-lateral amputees can be accommodated by these proposed guidelines. Consensus cannot be guaranteed by extending the study in this chapter either. As a result, a more practical solution is suggested by addressing the future viability of hosting a combined running race with both single and double amputees together. If any functional differences exist between them, the new proposals will address the single amputee category and separate research would then be needed to address the acceptability of prosthetics technology for bi-lateral lower-limb amputees.

6.8 CONCLUSION

There were several core aims of chapter 6. These were the investigation of the role, limitations to the ability of, and the acceptability of lower-limb running prostheses technology in competition with a disability. These would be used to help define guidelines to manage such technology within disability sport. The Delphi technique was selected through its ability to solicit expert opinion, anonymously, and in a developing area of expertise. High levels of consensus of 70% or greater were obtained for the studies aims from a purposively selected expert panel of 22 members. The Delphi process ran for three rounds.

It investigated what was understood, in the context of the research aims as acceptable or unacceptable with regards to the use of lower-limb sports prostheses in disability sport. It was felt that the technology employed in a prosthesis design could be unacceptable, even if this conflicts with new innovations which may help the athletes' quality of use or health. The need for ongoing vigilance was highlighted as a result. It was also implied that inequity in both the access and the cost of ESR technology raised concerns of acceptability but it is conceded within this study that these are difficult to regulate generally and within the scope of this study.

It is proposed that for reasons of acceptability, the prosthesis is defined as a 'restorative' form of 'equipment' used by an 'athlete' to take part in competitive disability sport. This means that a limit has to be applied to what the running ESR provides functionally even though this may conflict with new innovations designed to assist the athlete with their disability. In addition, the development of new technology is considered an integral sports ethos.

It was agreed that the appropriate limit of a running ESR's ability would be if the prostheses performance does not exceed that of a 'naturally determined' level. This was refined to reflect the limb to limb relationship in uni-lateral amputees.

It was agreed by the expert panel that running ESR technology does need to be monitored and limited in its performance to provide a fair sport to both its participants and its stakeholders. The rules and regulations that govern the sport are recommended to be revisited. To assist this, a series of guidelines to help regulate such technology has been proposed for further development. These include stride parameters of athletes under race conditions, whether double and single amputees should be separated from each other and further detail on how assistive technology should be assessed.

**CHAPTER 7: STRIDE CHARACTERISTICS OF
LOWER-LIMB AMPUTEE ELITE RUN RACES: A
CASE STUDY**

7.1 INTRODUCTION

Chapter 6 has provided proposed guidelines for the assessment of LLP use in competitive running. One of the recommendations was that “Lower-limb running prosthesis will contribute to a limb and stride length of no greater magnitude than that exhibited by the athlete’s biological lower-limb”. Whilst stride characteristics have been investigated in athletes with an amputation (Grabowski et al. 2009; Wilson et al. 2009), such studies typically use experimentation of test candidates under tightly controlled conditions and tests to objectively assess the balance of one lower-limb compared to the other. In addition, there are few studies which have assessed elite level athletes with an amputation (Bruggemann et al. 2007; Bruggemann et al. 2008). As a result, whilst observations surrounding stride mechanics in lower-limb amputees have generally taken place, evidence of this with elite athletes when performed under racing conditions has not been investigated. If asymmetries are shown to take place, the recommendations into the proposed guidelines in Chapter 6 should be expanded from merely considering a limb to limb threshold to acknowledging considerations of limb symmetry.

This chapter evaluates step inter-limb symmetry and step count data over race distances from race footage. This information will provide further insight into the current characteristics of T43/44 racing and ascertain how symmetry impacts athletes when assessed under competitive conditions

7.2 OBJECTIVES

This chapter investigates the following research objectives:

- a. To record inter-limb timing symmetry of elite T43/44 athletes competing over a fixed distance.
- b. To record the step count of elite T43/44 athletes competing over a fixed distance.
- c. To ascertain the severity of (any) lower-limb asymmetry in T43/44 racing.

7.3 METHODS

To assess competitive running under race conditions, quantitative based analysis using video footage or more qualitative methods such as ethnography could be used as viable techniques for obtaining context specific activity information. However, to maximise the raw data sample, multiple events would be required. As a result, video footage is the most feasibly accessible source of information. Real time analysis or observation is not realistic due to the speed and number of athletes involved in any one event. In addition, TV footage utilises the best field of vision of an event that would not be easily possible as an observer. The footage used for this study was derived from public domain sources including Paralympics TV (<http://www.paralympic.org/Videos>) via Youtube (www.youtube.com). The identity of the athletes in each piece of footage is a matter of public record.

There are 3 competitive running distances that occur in the current Paralympic Games format. These events are the 100, 200 and 400m running distances. However, the issue with such events and subsequent footage is

that due to the *switch between and panning of* multiple video cameras, the same athletes do not always remain in shot or in clear view. This makes any assessment of their stride characteristics problematic. The only event which minimises such issues is the 100m sprint event. As a result, only the 100m event is feasible for evaluation in this study. As remarked in chapter 4's study, the T44/T43 has been a combined classification event relatively unchanged in nature since 1976. As a result, both types of amputees are evaluated together in this study.

The video footage was checked to ensure that its televised recording speed was the same as the actual events results and it was also assessed for its visual quality to allow clarity of an athlete's ground impact. This ultimately meant only HD quality pieces had the desired resolution. The footage was then imported into the Quintic Biomechanics 9.0 software (Quintic Consultancy Ltd., Coventry, UK) which allowed frame by frame evaluation at the footages maximum specification of 0.04 second increments (25 frames per second). The analysis in this study is split into *step count* and *step symmetry*.

7.3.1 Step Count

When reviewing the footage to assess step count, the numbers of steps taken in the footage (by as many athletes that remain in shot for its duration) are recorded to achieve the 100m race distance. As the step count to achieve the 100m is never exact, the number of steps judged closest to the actual finish line is taken as the measured value.

The four events and its source evaluated for step count were:

- 1996 Paralympic Games T44/T43 100m Final
(<http://www.youtube.com/watch?v=WYxBWIY8iYc>)
- 2008 Paralympic Games T44/43 100m Final
(<http://www.youtube.com/watch?v=UDDhZx54Jy4>)
- 2011 IPC World Athletics Championships T44/43 100m Final.
(<http://www.youtube.com/watch?v=LTxypZ71-30>)
- 2012 Paralympic Games T44/43 100m Final.
(<http://www.youtube.com/watch?v=mcdUsMULNzo>)

7.3.2 Step Timing Symmetry

Whilst several videos were found to be available, only seven HD quality pieces of video footage had the visual resolution it was felt to be examined in close enough detail to evaluate the footfall data accurately. Of these, four pieces of footage were of qualification heats of both the 2008 and 2012 Paralympic Games. However, these were discounted from this analysis as it was seen that several athletes intentionally slowed down before the finish line. It is assumed that this took place due to either an athlete had estimated that their qualification was already secured or that they felt this had not been achieved and therefore gave up. This meant their stride would sometimes be seen to visibly slow down or shorten in stride length towards the end of an event. This made such data not representative of the events maximal effort and was therefore rejected. In addition, the athlete's reaction time to the starting pistol could not be evaluated as this exact moment was not within the unit of measurement of the analysis software or the footage.

The three suitable races evaluated for step frequency and symmetry were:

- 2008 Paralympic Games T44/43 100m Final
(<http://www.youtube.com/watch?v=UDDhZx54Jy4>)
- 2011 IPC World Athletics Championships T44/43 100m Final.
(<http://www.youtube.com/watch?v=LTxypZ71-30>)
- 2012 Paralympic Games T44/43 100m Final.
(<http://www.youtube.com/watch?v=mcdUsMULNzo>)

When reviewing the footage, a definition of ground impact was needed to record when a step had taken place. A ground impact was determined whereby the foot is seen to contact the ground just prior to the lower-limb beginning to bend at the knee or the prosthesis is seen beginning to compress

The greatest possible error of this evaluation is defined as half of the measurement unit. Therefore, potential errors in the step symmetry data are 0.02 seconds. The tolerance interval (or margin of error) is defined as ± 0.02 over the established measurements. However, due to the relatively large precision (due to the limitations of the footage), the largest error possible is defined here as one measurement increment of ± 0.04 . Therefore, only a change of greater than ± 0.04 from the previous data point is proposed to be significant in this study to then be defined as lower-limb asymmetry. Due to this relatively large tolerance, interval typical calculations such as the symmetry index (Noyes et al. 1991) would be misrepresentative of asymmetry so were not used in this study.

The athletes were classified as having three types of lower-limb behaviour. These are designated as lower-limb to limb symmetry (LS), lower-limb to limb asymmetry (LA), and random asymmetry (RA). LS is defined as a limb to limb timing within the measurement precision. LA is defined as a consistent limb to limb timing imbalance of greater than 0.04 seconds. RA is

considered a single event limb to limb timing imbalance of larger than 0.04 seconds.

7.4 RESULTS

7.4.1 Step Count

The recorded step count data is shown in figure 22.

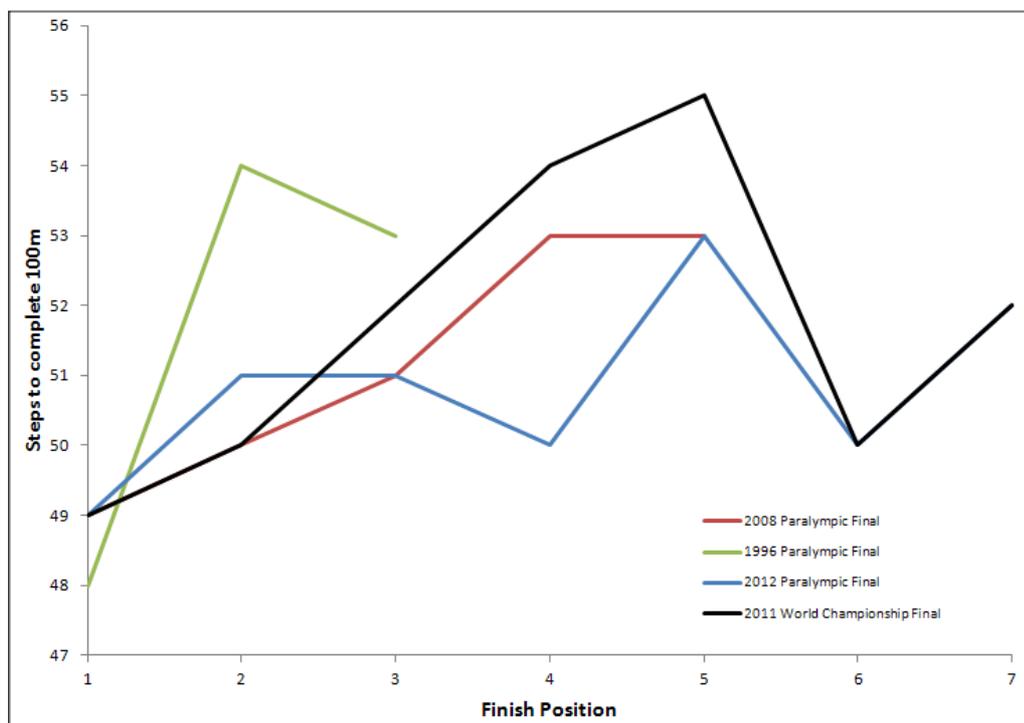


Figure 22. 100m T44/43 Step Count Data

It can be seen typically that in the race footage samples, the lowest step count is desirable to achieve the best possible finishing position. An event winner typically has no more than 49 steps with other medal winners typically a step behind. Interestingly, some slower runners in both 2011 and 2012 also exhibited a low step count yet performed poorly.

7.4.2 Step Symmetry

When reviewing the footage, three athletes gave an appropriate level of visibility in the 2008 event. There were also six from 2011 and four from 2012.

The three athletes' lower-limb to limb timing footfalls in 2008 are shown in figure 23.

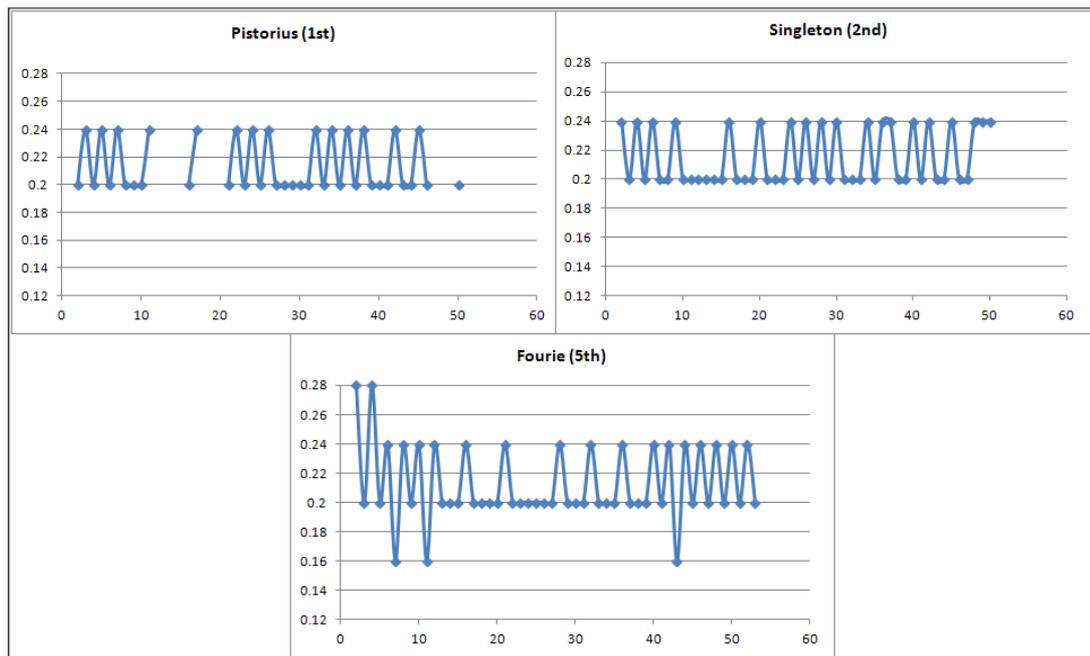


Figure 23. 2008 World Championships athlete gait symmetry summaries for athletes a) Pistorius, b) Singleton and c) Fourie.

Figure 23 illustrates the time taken for a foot's impact on the track to the alternate foot's impact upon the track. Both Pistorius and Singleton exhibited a lower-limb symmetry within the acceptable tolerance range of the study. However, Fourie demonstrated significant step to step RA in the first few strides of his race. It took him 4 steps to reduce to a more typical level of the LS seen with the other athletes. Fourie's mid section of his race shows an extremely symmetrical period of gait. Singleton demonstrated relatively consistent LS during his event. However, the last 3 steps of his event were slightly slower in duration.

The 6 runners from the 2011 World Championships are shown in figure 24.

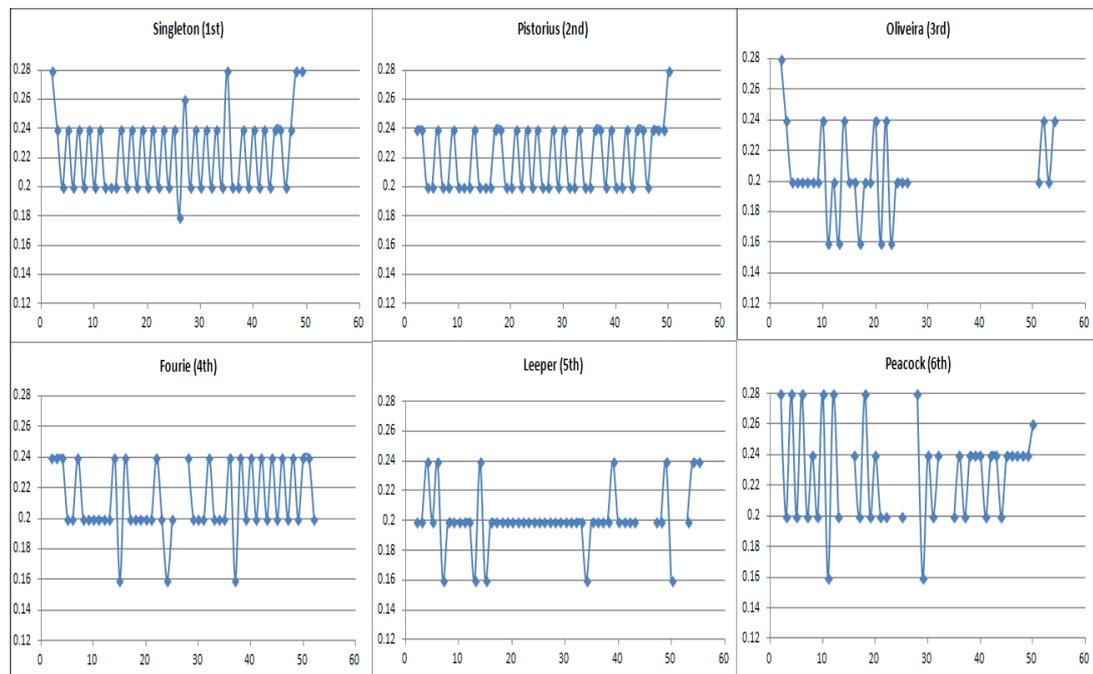


Figure 24. 2011 World Championships athlete gait cycle symmetry summaries for athletes a) Singleton, b) Pistorius, c) Oliveira, d) Fourie, e) Leeper and f) Peacock.

In this event it can be seen that bi-lateral amputees Pistorius (2nd) and Leeper (5th) exhibit very high levels of lower-limb symmetry. Singleton has brief RA at the start and again with his finish. Oliveira's run was only visible for the first half of the event. This aside, he exhibited RA at his start and sporadically throughout the first half of the event. Pistorius had relative LS but his last stride saw a one-off RA. Peacock had extremely consistent initial LA until the latter part of the race whereby his gait reflected LS.

At the 2012 Paralympic Games, 4 athletes produced clear line of sight for evaluation. These are summarised in figure 25.

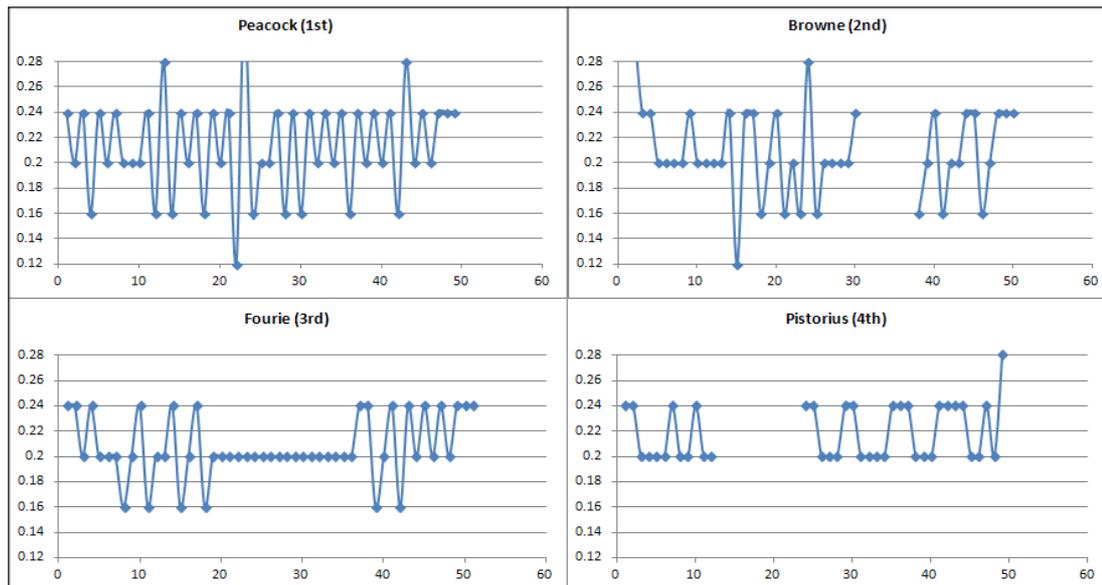


Figure 25. 2012 Paralympic Games athlete gait symmetry summaries for athletes a) Peacock, b) Browne, c) Fourie & d) Pistorius

Peacock showed great improvement in terms of his actual performance from 2011 by winning this event. However, his run still demonstrated significant RA. Unlike 2011, this took place towards the middle rather than the start of his race. Browne's run is perpetuated by RA throughout his event. Fourie exhibits RA after his start and towards the final stages of his run. Pistorius exhibits LS typical of both his 2008 and 2011 events.

The number of RA's of athletes from the 2008, 2011 and 2012 events are summarised in table 13.

Table 13. 2011 World Championship Performance

Athlete	Year	Place	Amputation Type	No. of RA Events (>0.04s)
Singleton	2008	2 nd	Uni-lateral	0
Singleton	2011	1 st	Uni-lateral	3
Pistorius	2008	1 st	Bi-lateral	0
Pistorius	2011	2 nd	Bi-lateral	0
Pistorius	2012	4 th	Bi-lateral	0
Oliveira	2011	3 rd	Bi-lateral	5
Fourie	2008	5 th	Uni-lateral	10
Fourie	2011	4 th	Uni-lateral	5
Fourie	2012	3 rd	Uni-lateral	6
Leeper	2011	5 th	Bi-lateral	5
Peacock	2011	6 th	Uni-lateral	13
Peacock	2012	1 st	Uni-lateral	16
Browne	2012	2 nd	Uni-lateral	9

The finishing position does not correlate to the number of RA events. Peacock has improved his finishing position performance in the 100m between 2011 and 2012 significantly yet still displays a large level of random RA between his two lower-limbs.

7.5 DISCUSSION

7.5.1 Step Count

The step count data suggested that at elite level, a low step count of no more than 49 steps is required to win the event. An assumption can be made that the step distance itself will vary throughout the event due to the rate of acceleration or speed at a given moment. However, the low step counts exhibited here suggest that step to step flight time is paramount. It is not clear of the performance of the start between the athletes. It is conceded that this may affect the step count, if the first step out of the start blocks is performed poorly or is very short.

Whilst the morphology and weight of all the athletes is not known in this study to ascertain other complicit factors, it is a reasonable assumption to recommend that stakeholders such as coaches could assess step count to ascertain the potential competitiveness of the athlete. A high step count could indicate a lack of ability or that their prosthesis requires assessment.

7.5.2 Step Timing Symmetry

This study shows that in the limited number of case studies available, randomised asymmetry behaviour does take place in elite 100m competition.

It is conceded that the limited 25 frames per second is not a high enough resolution to detect the exact level of asymmetry. However, the degree of consistent LA here seen in running is similar to those reported in controlled studies such as Sanderson & Martin (1996) which saw lower-limb step timing asymmetry of 0.02 sec at 3.5m/s and 0.03 at 2.7m/s. However, this study saw random asymmetry events of upto 0.08 seconds. From this it could be concluded that athletes under race conditions can create occasional

asymmetry that may not be reflected when running at either slower speeds, at a steady state or in non competitive environments. Differences in prosthetic length as the root cause as reported by Hafner et al. (2002) are unlikely to be the reason when the outcome is randomised asymmetry lower-limb timing.

Despite such asymmetry, there are several cases of randomised asymmetry performed by athletes in races. This does not seem to be a barrier to success as Peacock went from finishing 6th to 1st from 2011 to 2012 yet still exhibited a similar level of RA. However, what might be more important is *where* he exhibited the RA. In 2011 it was at the start whilst he was trying to accelerate. Yet in 2012 it took place when he was already closer to a steady state speed therefore it is proposed that the net loss in speed would be lower. The impact of randomised asymmetry within the 100m event and its impact on running speed are recommended for further study in the future.

The actual cause of RA's is unknown. However, in some cases, a root cause can be identified by qualitatively assessing the race footage. For example, Singleton in 2008 and both Singleton and Pistorius in 2011 demonstrated RA in the last few steps of their events. The reason for this could conventionally be assumed to be fatigue yet when looking at the video, both athletes were involved with a lunge for the line as both attempted to win. Figure 26 shows the position of the athletes when this occurred.



Figure 26. 2008 (above) 2011 (below): Singleton/Pistorius finish

It is proposed that the action of lunging for the line slows the stride slightly as the runner positions their torso. Singleton exaggerated this by so much in 2011 that he fell forwards after crossing the finish line.

When reviewing other athletes mid race asymmetry, the root causes could not be identified. It is proposed that the cases of RA need to be evaluated qualitatively alongside the quantitative data. The RA's at the beginning and end of races could be attributed to a poor or slow start with the finish RA being attributed to fatigue, falls, or torso lunging as per figure 26 above. However, it is possible that mid race RA's may not be the fault of the athlete

but equally in them dealing with their technology and the constraints of the event such as remaining within the lanes.

As an aside, when reviewing the race footage, all athletes exhibited behaviour of start with an acceleration from rest, the maximal speed being obtained, a brief speed maintenance phase and then a level of evident fatigue. However, in two separate cases, there was visually unusual behaviour by an athlete in the 100m. Bi-lateral athletes, Pistorius in 2008 and Volpentest in 1996 exhibited unusual accelerations through the field. These took place around the midpoint for Volpentest and within the last 3 seconds of the event for Pistorius. These are shown in figures 27 and 28.



Figure 27. 2008 Pistorius Acceleration

At approximately half distance, Pistorius is lying in 6th position. By 7.7 seconds he is in 4th and already reducing the distance to the runners in the lead. By 10.2 seconds he is in 2nd. Pistorius went from being 4th into challenging for the lead in just 2.5 seconds (or 7-8 steps). The 1996 event is shown in figure 28.

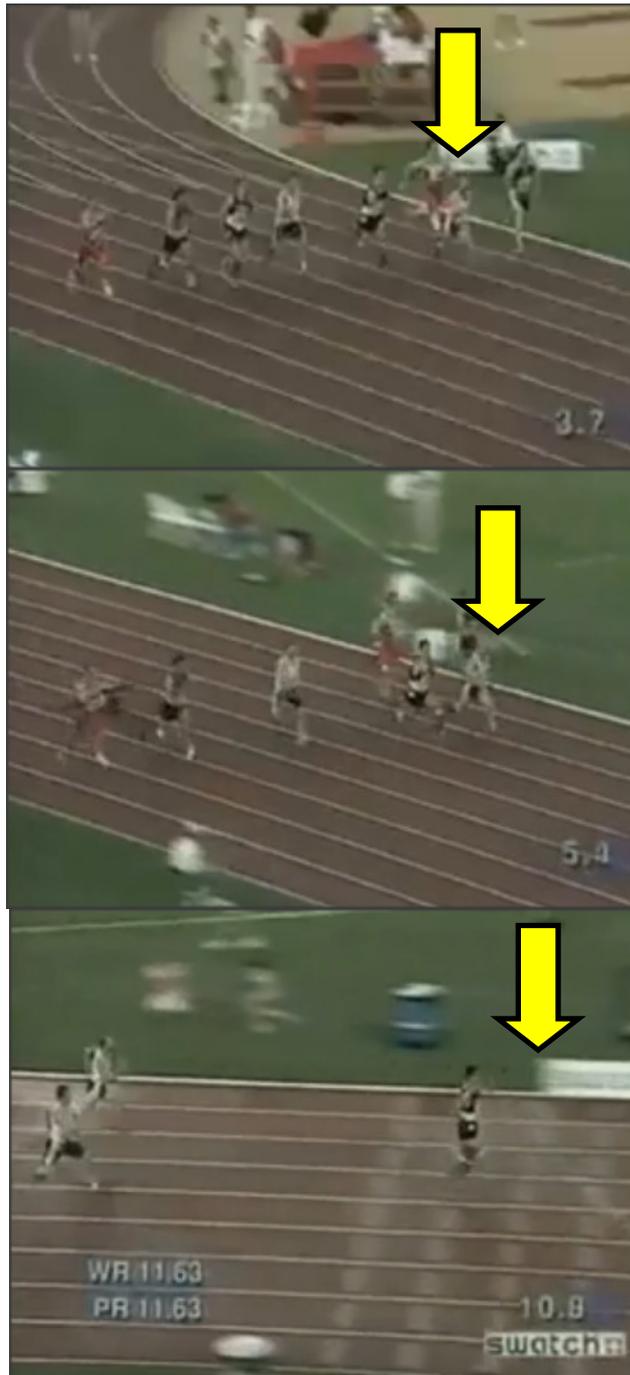


Figure 28. 1996 Volpentest Acceleration

In figure 28, Volpentest enjoys a start similar to the rest of the competitors. At 5.4 seconds (and approximately halfway duration) he is in 2nd but still accelerating. By 10.8 seconds he is clear, winning by 6-7 metres.

The reason for such a dramatic acceleration once the race was already underway is not clear. A potentially performance enhancing effect that may be a reason for this was recently proposed by Noroozi et al. (2012) of which this thesis author was a co-author. A 'dynamic elastic response to timed impulse synchronisation' (DERTIS) has been proposed to potentially enhance an amputees running if they are at a steady state speed and possess symmetrical lower-limb dynamic properties. It was demonstrated by Noroozi et al. (2012) that if the natural characteristics of a system are identified and synchronised with the physiological gait behaviour of a runner, performance enhancement can occur, resulting in more potential energy being stored in the system. This can later be recovered and will increase vertical flight time. Ultimately, a bi-lateral amputee athlete with near symmetrical gait could potentially recover the stored energy during the steady state or latter phases of a running event and this would be more beneficial the greater the proportion of steady state speed that took place in a running event.

The limitations of the DERTIS proposal are that to date it has not been replicated using human participation. This effect may only be unique to disability sport and sprung prosthesis since vertical impulse has been proposed as being potentially a disadvantage with able-bodied sprinters (Hunter et al. 2005). If this is true, this is significant because if both Noroozi et al. and Hunter et al. are correct, it means that an athlete with a uni-lateral amputation should not get any benefit from DERTIS (due to still having one intact limb) whereas the bi-lateral amputees could. If any disparity existed between bi-lateral and uni-lateral athletes, such an effect would constitute an unfair advantage possibly unique to one type of amputee over another. This effect is recommended being investigated further.

In summary, this study sought to ascertain if limb to limb asymmetry existed in current elite racing. This study demonstrated that it does so and can be classified as:

- lower-limb asymmetry that is consistent
- asymmetry that occurs randomly.

Consistent asymmetry was not clearly obvious due to the measurement resolution feasible using the assessment methods in this study. This is not to say that it does not exist, but that it is not obvious within the margin of error. However, randomised asymmetry was still seen to occur. The cause of this could not easily be explained but that root causes are proposed here as:

- a. The fault of the prosthetic design for the athlete
- b. A conscious or unconscious tactical decision of the process of gait on the part of the athlete when running.
- c. Unclear events due to unknown stresses of the racing experience.

The responsibility for cause a. is that of the athlete and therefore the proposed guidelines in Chapter 5 should not attempt to mitigate for this. Examples of cause b. such as finishing dips were given in this chapter and would also be the responsibility of the athlete. Again, the acceptability guidelines should not mitigate for an individual's personal strategic decision making during a race. However, there were also cases of c. This occurred in more than one athlete and would therefore suggest asymmetry is a key characteristic within the event and should be monitored.

It would have been ideal if uni-lateral and bi-lateral athletes could have been separated but the limited sampling of bi-lateral athletes could not support this conclusively. However, whilst uni-lateral athletes could occasionally exhibit relatively symmetrical limb to limb behaviour when racing, this was not the typical norm. However, in the few bi-lateral athletes evaluated here, they were typically always symmetrical (albeit within the measurement resolution

of this study). As a result, it is proposed that the impact of inter-limb symmetry, as well as merely adopting the limb to limb functional threshold guidelines in Chapter 6, are relevant when proposing guidelines for acceptability in this project. However, whilst it is argued here that an acceptable amount of lower-limb asymmetry is undesirable; this experiment does not establish what would be an appropriate range due to the limited athlete sample.

7.6 RECOMMENDATIONS

This study should be expanded in the future to cover a larger sample of athletes and more competition footage to support these findings. In addition, the measurement resolution to identify a ground footfall should be improved beyond that employed in this study (0.04 seconds). This would be dependant of the quality of the TV footage in the future.

There were two cases of unusual accelerations or speed maintenance phases of bi-lateral amputees in races. The simulation of the proposed DERTIS effect by human participation is proposed necessary for further study to ascertain if this was the root cause in these cases. This has not been fully pursued within this thesis at this time as this aspect is already being undertaken predominantly by this projects first supervisor (Prof. Siamak Noroozi) and assisted by other contributors, including this thesis author.

7.7 CONCLUSION

It was seen that within the samples in this study, a low step count of <50 steps is recommended for being successful in the 100m T44/43 event. In

addition, flight time between steps would also seem to be a key performance indicator.

It was seen that randomised asymmetry took place in athletes in 100m lower-limb amputee racing in 2008, 2011 and 2012. There was evidence of consistent lower-limb step timing asymmetry but little greater than 0.04 seconds. There were cases of randomised limb to limb asymmetry that occurred in several athletes that could not always be explained. The pragmatic proposal is not only to place a performance ceiling when defining guidelines for prosthesis acceptability, but also to allow a range which incorporates a minimum value too. As such inter-limb symmetry guidelines are also recommended to be included in any proposed acceptability guidelines.

This study has demonstrated that the inclusion of limb to limb stride characteristics proposed in Chapter 6 should be included in the final proposal of such guidelines.

**CHAPTER 8: THE FUNCTIONAL DIFFERENCES
BETWEEN SYMMETRICAL AND
ASSYMETRICAL LOWER-LIMBS: A CASE
STUDY**

8.1 INTRODUCTION

Chapter 6 proposed guidelines for the assessment of LLP use in competitive running. A key recommendation was to potentially use a biological limb as a reference for a prosthetic limb to be directly compared against. It was also found that LLP were deemed a form of equipment to be judged philosophically as a separate entity from the human body. A functional change on the part of the technology is then used to determine its inclusiveness (or not) in the sport.

Chapter 6's outcomes would not be easily applied to bi-lateral amputees as they do not have a biological limb to act as a baseline reference to compare their prosthetic limbs against. However Chapter 2's literature review remarked that both bi-lateral and uni-lateral amputees still have historically competed alongside each other as part of a combined T44/43 classification at the Paralympic Games. Whilst the current IPC's regulations do cover the determination of limb length for bi-lateral amputees, they do not cover the functional performance of such limbs. As a result, rather than immediately pursue an assessment protocol solution, the research investigated whether bi-lateral and uni-lateral runners have functional differences that would provide basis for separating them in competition.

8.1.1 Differences between Uni-lateral & Bi-lateral Lower-limb Amputee Runners

Accepting that running is a specialised activity and that as noted earlier in this thesis that ESR prosthesis have only been evident since 1988, specific research comparing single and double lower-limb amputees in this area is understandably limited in availability. Several studies have compared *uni-lateral lower-limb amputees to able-bodied runners* (Grabowski et al. 2009; Umberto et al. 2006; Buckley 1999; Prince et al. 1992; Czerniecki & Gitter

1992; Czerniecki et al.1991). There are also studies that have compared *bi-lateral lower-limb amputee* runners to *able-bodied* runners (Weyand et al. 2009; Bruggemann et al. 2008). The lack of published research regarding bi-lateral lower-limb amputee runners was acknowledged as a limitation in the understanding of amputee locomotion by Lechler and Lilja (2008). The recent publications that have addressed bi-lateral lower-limb amputee running have done so in an attempt to directly address the controversy surrounding Oscar Pistorius (Weyand et al. 2009; Bruggemann et al. 2008). In such examples, a single bi-lateral lower-limb amputee test subject was used and was typically a case study approach involving Pistorius himself. More recently, a study by McGowan et al. (2012) has attempted to compare both uni-lateral and bi-lateral amputees to able-bodied running participants and use at least two of each test subject type. In all of these studies, differences both in terms of running gait and muscular work compensation have been reported as well as those remarked in Chapter 7's analysis of step timing performed by both types of amputees in elite races.

The majority of studies assessing running amputees use comparably low speeds of less than 5 metres per second (Prince et al. 1992; Czerniecki & Gitter 1992; Czerniecki et al.1991). Studies which examine running with an amputation at 100-400m event specific speeds are extremely limited in number (Bruggemann et al. 2008; Umberto et al. 2006). In addition, it has been proposed that the properties of a biological limb alter in stiffness with increasing running speed (Hafner et al. 2002). However, with amputees, stiffness in a biological limb increases with speed but decreases if the participant uses a lower-limb ESR (McGowan et al. 2012). Ultimately, the speed (or the result of that speed), is of key importance when comparing biological to artificial limbs. However, no study to date has compared *both* uni-lateral and bi-lateral lower-limb amputees together when running at event specific elite competition speeds. Bi-lateral lower-limb amputee race speed assessment has been attempted on a track (Bruggemann et al. 2009) and more commonly using a treadmill (McGowan et al. 2012; Weyand et al. 2009). The treadmill does not take into account the aspects evident in a race

such as the starting blocks, any bends and aerodynamic considerations. As such, context specific comparisons of the actual loads and demands of events such as the 100-400m have not been evaluated.

When considering the differences between single and double lower-limb amputees, such comparison has typically been proposed through differences in physiological markers such as oxygen uptake (Weyand et al. 2009; Bruggemann et al. 2008), biomechanical comparison such as limb path and ground reaction forces (Weyand et al. 2009), lower limb stiffness (McGowan et al. 2012) and metabolic energy costs (Weyand et al. 2009).

It could be proposed that study of uni-lateral lower-limb amputee athletes is ideal as both prosthetic and biological limbs can be compared simultaneously. Such a hypothesis has only been evaluated from a physiological perspective. This was proposed by Grabowski et al. (2009). However, with uni-lateral runners, compensation of the lack of muscular work of the prosthetic limb has been shown to be performed by the non-amputated limb by extra work at its knee and hip (Czerniecki & Gitter 1996) and that a biological limb can be adjusted unconsciously to maintain a runner's step frequency (Sanderson & Martin 1996). The Grabowski study (et al. 2009) insinuated an improved understanding of all running amputees who use ESRP's through its testing. However, this study only tested uni-lateral amputees to determine their conclusions and ultimately still confirmed that limb interdependence was probably a factor. In addition, the physiological energy cost is reported to be higher in an amputated limb using a prosthesis compared to a biological limb (Czerniecki & Gitter 1996). A bi-lateral amputee has lost two limbs, which would suggest an increased metabolic cost over that of a uni-lateral amputee as physiological demand is greater with the level of amputation to the overall body (Lewis et al. 1996). To date, only one study exists in the literature that has compared both amputee types and this study did not evaluate metabolic differences between amputee types. However, there are opposing arguments that a bi-lateral lower-limb

amputee has a lower (Bruggemann et al. 2008) or higher (Weyand et al. 2009) overall metabolic cost than the able-bodied equivalent. The key difference in these studies is the type of control group the amputee is compared against. Either way, due to the lack of published knowledge, an evaluation of the uni-lateral to explain the possible ability of a bi-lateral would seem to be inappropriate.

Aside from using physiological or biomechanical characteristics to determine the differences between amputee types, a mechanical approach has also been proposed (Noroozi et al. 2013; Noroozi et al. 2012). The Noroozi studies proposed that the response of a LLP could be synchronised with the response of a runner's body mass and step frequency when running to enhance vertical displacement. This effect was defined as the 'dynamic elastic response timed impulse to synchronisation (DERTIS)'. The Noroozi studies demonstrated through simulations that by synchronising the ground impact, athlete's mass and the subsequent response of ESR's, the vertical displacement could be enhanced in the same way that a gymnast gains height when bouncing on a trampoline. Alternatively, by not synchronising these elements (or 'damping' them by bouncing out of phase), the vertical displacement would be decreased. The Noroozi studies postulated that a bi-lateral amputee using ESRP's with perfect limb to limb symmetry could ultimately be performance enhanced under certain conditions by obtaining benefits that a uni-lateral amputee could not equally receive. This effect would achieve an increase in vertical displacement which would hypothetically increase the flight time of a runner. This flight time aspect with amputee runners has been referred to as a 'float phase' (Umberto et al. 2006). It has been suggested that with lower-limb amputee running that step frequency is primarily used to increase speed (Enoka et al. 1982). However, more recent research has instead claimed that stride length is of greater value (Sanderson & Martin 1996). Chapter 7 of this thesis illustrated the importance of lower step counts by race winners. If the DERTIS effect were possible, this would provide an argument for separating the two amputee types from each other in competition. However, the limitations are that the

effect has not yet attempted to be replicated using human participation. In addition, it was conceded that any changing of boundary conditions (such as those caused by human gait) could reduce the effect.

Whilst a case could already be established to separate the two types of amputees based on reported differences in terms of their physiological and kinematic differences, this chapter attempted to do so when adopting Chapter 5 recommendations that the inclusion of prosthetics technology should centre on the direct influence of that technology itself. It also focused on maintaining symmetry of functionality between lower-limbs in response to the use of energy storage and return (ESR) technology. The impact of changing the technology itself to create varying degrees of lower-limb functional symmetry was used as a basis of this investigation.

8.2 OBJECTIVES

This chapter has the following research objectives:

- a. To distinguish any differences between symmetrical and asymmetrical sprung lower-limbs in response to direct changes in ESR technology when subjected to cyclic impacts under controlled conditions.
- b. To propose if bi-lateral and uni-lateral amputees should be separated when competing in running races at the Paralympic Games due to key differences created by changes in lower-limb prosthetic function.

8.3 METHODS

Whilst running would be the most context specific method for evaluation, testing would require multiple cameras and large assessment areas. Alternatively, treadmills could be used to achieve a context specific activity but they do not allow for an instantaneous change in running speed should a participant wish or safely need to. It is felt that safety is paramount when encouraging motion using intentionally imbalanced lower-limbs. However, to compare the effect of ESR technology, the selected method would only need to simulate ground limb to limb impacts as opposed to full gait cycles. As a result, this experiment attempted to create cyclic limb to limb impacts within a constrained environment that was easily controllable by participants.

A suitable solution in generating limb-to-limb impacts was proposed by performing jogging on the spot. The jog on the spot tests (JOST) were intended to replicate an alternate single lower-limb impact coupled with the ability to easily track the resultant changes in limb response. This was not proposed as a means to replicate running but more so to replicate cyclic ground based impacts. Jogging on the spot has been undertaken within a controlled and confined environment and has been used for limb to limb assessment for patients with likely lower-limb asymmetry due to hip replacement (Basse et al. 1997) or more typically as a warm up strategy prior to other activity (Sharma et al. 2004). A participant jogging on the spot will still produce exchanges between potential and kinetic energy as they launch from the ground, achieve upward thrust, and reach the highest point, before then falling to earth.

Unlike running, because leg sweep angle and a directed forward thrust do not take place, any change in the participants' height would be predominantly vertical. The limitations of such technique is that the level of footroll seen in running gait (Mero 1992) are likely to be smaller as forward motion is not undertaken. When running, the exact path of the centre of mass of a body

has been proposed to be a combination of leg stiffness and sweep angle and landing velocity (McGowan et al. 2012). By performing a test and assessing a fixed spot, the vertical displacement and speed of this is as a result of the footwear's mechanical properties and minimises the impact of the biomechanics of the leg swing and sweep. This test method is assuming a response to a ground impact based upon the spring like nature of a lower-limb. The limitation by the participant remaining on the spot means does not account therefore for any impact of input such as power generation caused by the foot roll of the foot. However, since energy generation in sprint runners has been credited as being derived from the ankle and the knee (Mero 1992) this test still maintains that relationship.

The outcome measure in this study was determined as a person's change in vertical displacement and their velocity of fixed points. This change is typically caused by the transfer of potential energy to kinetic energy of a moving body (Hibbeler 1997, p.172) driven by the legs (Mero 1992). Vertical displacement in itself is considered important in running as this provides a 'float phase' - i.e. when neither feet are touching the ground (Umberto et al. 2006). A float phase ultimately contributes to the distance travelled between steps when running. Along with displacement, the speed of a fixed point indicated its movement behaviour. A change in speed of a limb could indicate a compensatory effect or the benefits of impulse synchronisation, unique to using ESRP's when running as proposed by Noroozi et al. (2012).

8.3.1 The JOST Protocol

The JOST test was performed by a participant jogging on the spot. As a result, this involves an impact applied to each alternate limb independently and forms the basis of any limb to limb comparison.

A sole participant was used for this experiment as a case study. A unique approach is proposed by using an able-bodied participant who is wearing energy storage and return footwear to simulate ESR prostheses. A non-disabled participant allowed for a standardisation of impact load and natural limb-limb to performance whilst then creating the opportunity to adjust either legs mechanical properties. This would not be possible with participants who are disabled and therefore maintained the focus on the impact of the technology itself – as per Chapter 6’s findings. Whilst it could be argued that using athletes with lower-limb amputations as test subjects would be more representative of the end user, this experiment places its emphasis on the performance of the technology and the robustness of the JOST test rather than the specific nuances of a amputee test population. As a result, at this preliminary stage, amputees were not needed.

The case study participant was a current able-bodied amateur athlete with a history of competitive running participation in events ranging from 100m up to the marathon distances. The participant used energy storage and return footwear (ESRF) which would allow the simulation of relative changes in lower-limb performance and symmetry. The footwear (Tramp-it BV, Den Haag, The Netherlands) is shown in figure 29.



Figure 29. Energy Return Footwear

The blade of the ESRF is manufactured from a toughened steel material. The boots are worn by securing several ratchets and straps along with laces. These heavily restrict (but likely do not fully remove) the ankles impact.

Because only absolute marker response and repeatability of each limb was being checked, any limb to limb length discrepancy was not deemed as a primary concern for these trials. Conventional athletes with a uni-lateral amputation would also have a limb length discrepancy as the amount of compression an energy return prosthesis would be subjected to, would differ at various running speeds throughout their race. This could also be compounded if an amputated limb's stump would be subjected to 'pistoning' (or undesirable vertical movement) inside a prosthesis socket. As a result, exact lower-limb length symmetry at all times is not achievable if using ESR technology.

The JOST was performed by a participant initially standing on both feet. When the test started, the participant began to jog on the spot, landing each time on alternate legs. Chapter 7 indicated that step timing was reasonably constant during elite running with an amputation. As a result, the JOST were undertaken at a fixed footfall frequency to isolate any vertical displacement change. As such, the footfall frequency was defined through use of a metronome for the participant to follow as a guide. The metronome used an audible alarm to signify a constant step frequency of 3Hz. This frequency is less than those recorded in high speed sprinting shown in Chapter 7 to be 4-5Hz but pre experiment trials determined that this frequency was the fastest that could be safely undertaken by the participant. The test duration was 10 seconds. The floor was marked using tape to provide guidance lines for the participant to ensure they maintained a repeatable landing position to help minimise horizontal drift. This is shown in figure 30.



Fig 30: JOST Test Experiment

Five different asymmetrical limb to limb conditions were assessed using the ESRF. This was achieved by adjusting the stiffness settings of each ESRF by altering the blade length. These five conditions are shown in table 14.

Table 14. Energy return footwear settings

Condition	Left Shoe Setting	Right Shoe Setting
1	Long	Long
2	Short	Long
3	Short	Short
4	Long	Short
5	Long (reversed)	Long (reversed)

Whilst bare feet could have been used to identify any natural asymmetry in the participant's limbs, Condition 5 was instead used to account for any such issues by switching the energy return springs over between the shoes.

Each symmetry condition was tested individually and cycled sequentially with a 5 minute seated recovery rest period to allow for the shoes to be mechanically adjusted and to minimise the participant to unconsciously compensate for each condition. In total, 5 trials of each symmetry condition were undertaken meaning for the purposes of this study, 25 tests in total were completed.

The tests were filmed using a single camera recording at 210Hz. Lower-limb vertical displacement and speed was recorded for analysis. The metrics were captured through the use of 8 light reflective markers. These were placed on the tip of the ESRF blade, top of the ESRF boot, mid shin, and knee on both legs. Light reflective markers have been used when assessing the motion of athletes with a lower-limb amputation (Bruggemann et al. 2008). The vertical displacement and speed of the knee markers were used as the key reference to track lower-limb behaviour as each test is performed. The other markers acted as back ups on any runs that suffered from marker tracking loss. A centre of mass marker was initially considered for use but was later rejected as pilot testing revealed that the participant's arms would cross in front of their chest during the trials thereby obscuring the markers tracking path. This problem increased with higher intensity efforts. The head and neck region was also proven to chaotically move in a manner. It is conceded that the knee markers, whilst not a fixed point of reference, would still allow for lower-limb comparison.

The footage was calibrated and analysed using Quintic motion analysis software (Quintic Consultancy, Coventry, UK). The data was then smoothed using Butterworth filters within the software.

8.4 RESULTS

The mean step frequency and displacement results of the JOST are shown in Table 14. The knee marker data is contained in appendices B.1. The *Coefficient of Variation* is used as a measure of absolute test consistency and is calculated as Standard Deviation divided by the mean and multiplied by 100. This provides the measure as a percentage.

Table 15. JOST Test Repeatability

Condition	Mean Step Frequency (Hz)	CV (%)	Leg to leg knee marker diff. (m)	Dominant limb by displacement
1	3.00	1.3	0.00	Symmetrical
2	3.00	1.2	0.04	Left
3	3.00	0.7	0.01	Marginal asymmetry
4	3.01	1.4	0.05	Right
5	3.01	1.1	0.01	Marginal asymmetry

It can be seen in table 15 that all the tests were at or extremely close to the 3Hz target with very low coefficient of variations demonstrating high repeatability of the trials and a sustainable effort despite any levels of imposed asymmetry. There are also clear differences between symmetrical and asymmetrical conditions with a 40-50mm difference in obtained knee marker height symmetry. Whilst the participant was non-disabled, they were still able to produce a significant limb to limb asymmetry.

In addition to the displacement, the mean velocity of the left and right limbs being raised and lowered whilst undertaking the JOST is shown in table 15. The low to high phase is the direct response to the ground impact of the mechanical properties of the energy return technology blade whereas the high to low is under the control of the participant to return the limb to the point of ground impact. The *Symmetry Index* (SI) was used to define the level of discrepancy from limb to lower-limb as described by Barber et al. (1990) as: *Non dominant leg/dominant leg x100*.

The units for the movement of markers were measured as *metres per second*.

Table 16. JOST Test Symmetry

Condition	Left		Right		Mean of Up/down Knee Speed		Symmetry Index (%)
	Mean Velocity – High to low (m/s)	Mean Velocity – Low to high (m/s)	Mean Velocity – High to low (m/s)	Mean Velocity – Low to High (m/s)	Left	Right	
1	0.51	0.30	0.37	0.40	0.41	0.39	95
2	0.48	0.27	0.46	0.45	0.38	0.46	82
3	0.48	0.40	0.47	0.42	0.44	0.45	99
4	0.50	0.45	0.37	0.31	0.48	0.34	72
5	0.48	0.26	0.41	0.26	0.37	0.34	91

Conditions 1, 3 and 5 were intended to be symmetrical and the overall means speeds does show a relative symmetry between conditions 1 and 3. Condition 5 showed a slightly wider asymmetry. Condition 5 should ideally also be the same as condition 1. Its only difference is that the blades have been switched over between the shoes. It did not produce the same results, thereby suggesting that a natural asymmetry between the participant's limbs exists or that the ESRF blades are marginally different in their properties.

The greatest range between the 5 conditions in knee marker speed is when the limb moves from the lowest point to its highest point. The knee speed is moving faster when the leg is returning to the ground. The only exception to this was the right leg of condition 1 which was nearly the same speed between raising and lowering the limb.

The typical differences in marker tracking seen between conditions 1-5 are shown graphically in figure 31.

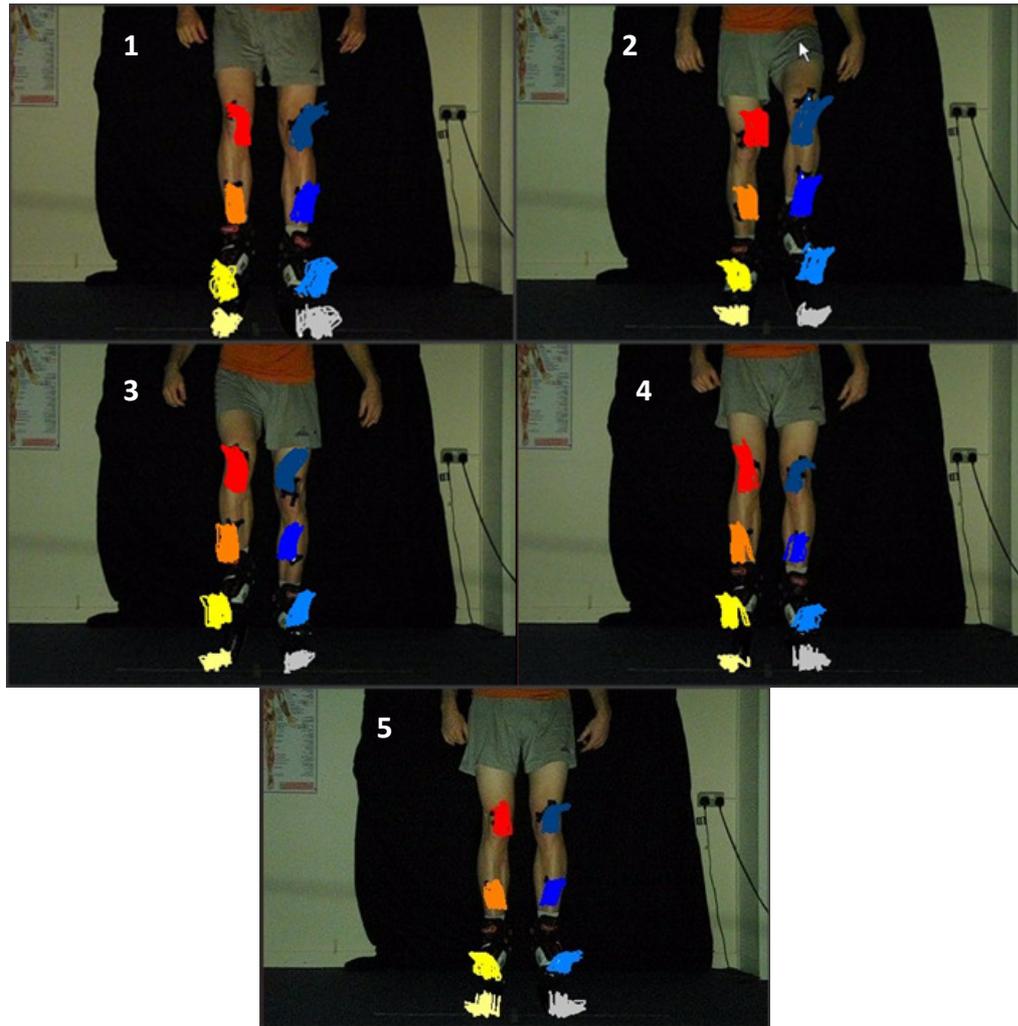


Figure 31. JOST, Test 1-5 (left to right)

The path traces of each marker are shown in figure 31 with a different colour. It is seen by the markers used in these tests that in asymmetrical conditions the marker stroke increased the higher up the leg it is. The symmetrical condition has a much more even stroke range of marker through the whole lower-limb. This shows that some compensation in movement (not clearly visible in this frontal view) likely took place. The only way the variable marker stroke in the asymmetrical could have had a longer stroke at the knee (but less at the foot) would be by changing the leg effective length possibly by utilising the joints such as the ankle.

The marker traces at the knee in the examples in figure 31 demonstrate that the knee follows a slightly arc trajectory.

8.5 DISCUSSION

By imposing a fixed step frequency, it was assumed that the participant would either not be able to maintain 3Hz or that they would adjust for any asymmetry to re-establish symmetry between the 2 lower-limbs. It can be seen in the results that the step rate was both maintained successfully and that the participant could cope with the level of asymmetry in any of the assessed conditions. However, to do so, the participant had to vary the speed of the limb stroke to account for changes in the upstroke behaviour. In the case of the symmetrical lower-limb conditions the limb to limb speed was symmetrical between both legs. It would be recommended to assess a unilateral amputee to see if they also vary their limb downstroke if step frequency is at a constant.

To counter any limb to limb difference in performance, the participant could have theoretically changed the footwear's response by pivoting at the ankle joint to change the blade length and thus its stiffness. This may still have occurred to some degree but this test indicated that the participant was still unable to fully counter the basic asymmetry of conditions 2 and 4. The fact that an asymmetrical condition required an adjustment of limb path speed (that the symmetrical conditions did not) suggests a key functional difference between such types of arrangement. An asymmetrical lower-limb arrangement would require extra energy on the part of the athlete to be expended that the symmetrical case would not have to in the form of acceleration of the lower-limb. This does not prove that one condition is superior to the other. It does imply that they can be shown to be clearly functionally different and under different conditions from each other.

It is also noted that the overall mean speed of symmetrical conditions 1 and 3 demonstrated a relative symmetry yet condition 5 did not. Condition 5 is the same as condition 1 but with the blades switched over. It is proposed that

this arrangement exaggerated (or that conditions 1 and 3 shrouded this to a lesser extent) the natural limb to limb asymmetry of the participant. However, bearing in mind that the marker displacement and speed results of conditions 2 and 4 were virtually inverse of each other, suggests that the participant's natural imbalance was still very small.

The provision of symmetry indices data from these trials is useful as, like Chapter 7, provides a case that a *symmetry threshold* could be established between types of amputees as an objective means to separate them. A robust sample would be needed to provide an exact point of this threshold as well as the exact criteria to be compared using the symmetry indices.

This experiment did not investigate the impact of fatigue to lower-limb symmetry. This may well be a factor in longer length trials. It would be interesting to investigate the fatigue behaviour between lower-limbs when limb to limb ground impact testing is performed. This would be useful when accounting for the longer duration events such as the 400m.

8.6 CONCLUSIONS

This chapter sought to ascertain if there were any differences between symmetrical and asymmetrical sprung lower-limbs in response to direct changes in ESR technology when subjected to cyclic impacts. In this case study, it was shown that the human body could not fully filter out such changes and attempted to adjust for any discrepancies via unconscious adjustment of lower-limb speed. It is proposed that any acceleration of a lower-limb that an asymmetrical user has to undertake is costing them energy that a bi-lateral candidate does not. It is assumed that any energy cost within a racing environment to an athlete would cause them to fatigue before others or would provide penalties to their effective running gait. Either

way, it is not known if this change is advantageous or disadvantageous but does highlight a key functional discrepancy between such cases. As a result, it is proposed that it is not appropriate for locomotively different lower-limb persons to compete alongside each other.

8.7 LIMITATIONS

By using a single candidate, the findings in this study cannot be unilaterally assumed to take place in all T44/T43 major competitions. However, it does now provide a case to investigate a larger amputee based sample.

Motion capture marker placement was suitable to detect lower-limb differences in this study but should be expanded to include multiple fixed points of reference as well as both relative and absolute marker information. Such data was not available using the technology in this study.

8.8 ACKNOWLEDGEMENTS

Thanks go to both Bournemouth University staff: Associate Lecturer Shelley Broomfield & Lecturer Andrew Callaway, who assisted in the data collection of the jog hop tests in this chapter.

CHAPTER 9: THE NATURE OF ENERGY STORAGE & RETURN PROSTHESES

9.1 INTRODUCTION

The literature review in Chapter 3 remarked that an energy return prosthesis was a simple spring (Nolan 2008) and passive in nature. Chapter 6's Delphi study recommended that a limb to limb comparison has been agreed by the stakeholders as a preferred regulatory guideline. To do this, the nature of the ESRP was investigated to see what its behavior is when in actual use.

An ESRP should be designed with the requirements of high speed running in mind. When isolating the limb itself when running, one of its key performance indicators has been proposed as limb stiffness (Nolan 2008; Bret et al. 2002). Whilst stiffness is important as a starting point for prosthesis prescription (Lechler & Lilja 2008; Personal communication, Blatchford & Sons, January 2007), it is not a destination in itself. A patient's anecdotal feedback and qualitative outcome measures are still used extensively to determine prescription (Laferrier & Gailey 2010). Ultimately, high stiffness is integral to sprint running performance but increasing limb stiffness considerably may be made at the cost of energy efficiency (Nolan 2008).

With a non-disabled participant, it has been reported that stiffness of the biological lower-limb typically remains the same upto moderate running speeds due to the leg spring length changing to compensate (Brughelli & Cronin 2008) and has been shown to increase with higher speeds (McGowan et al. 2012; McMahon & Cheng 1990). However, in the case of lower-limb sprinters with a below-knee amputation, it is assumed that the disabled runner cannot modulate lower-limb mechanical properties of their prosthesis due to its passive nature and the lack of an ankle and/or knee (Nolan 2008). If an energy return prosthesis is inherently a spring of fixed mechanical properties, it will have a uniform stiffness (Nolan 2008) and could be calculated using a force-displacement curve (Hafner et al. 2002). However, there has been a reported variability in the lower-limb stiffness of

amputee prostheses when running (McGowan et al. 2012). If a uniform stiffness was evident, then prescription of ESRP technology could be made based upon the athletes mass and expected bodyweight impact of their chosen event. This would then indicate the required stiffness of the prosthesis required and make regulation of LLP a non invasive, low exertion practice. It was investigated whether this is the case. Some of this chapters content has seen peer review via journal publication (Dyer et al. 2013) and is contained within Appendices F.

9.2 OBJECTIVES

This chapter investigated the following research objectives:

- a. To investigate the nature of ESR technology behavior at the point of ground contact.
- b. To investigate the ESR technology stiffness characteristics.
- c. To propose whether prescription of ESR technology could be made using non-invasive means by assuming a linear-like behavior of the prosthesis spring.

9.3 METHODS

Objective a. was addressed by performing run tests using ESR technology when running at the highest possible speed. This method provides specific assessment for the technology as it would be used.

Objective b. assessed the linearity behavior of ESRP's when loaded with increasing force.

9.3.1 Energy Return Technology Run Tests

The behaviour of ESR technology was investigated by undertaking a series of steady state running test trials. These were performed to simulate the ground contact behaviour of energy return technology when performing context specific activity.

A non- disabled participant performed the trials. The participant was a current amateur athlete with a history of competitive running participation in events ranging from 100m upto the marathon distance. They performed a self-selected warm up prior to the tests and gave written consent for this experiment.

For the run tests, the same participant and energy return footwear in Chapter 8's investigations were used. Use of this footwear and an able bodied participant was considered appropriate as it is adequate to demonstrate energy storage and return behaviour and that use of an amputee would not add value at this stage. Two different stiffness settings of the footwear were used to provide variety to the technology's response. This was achieved by a fixed adjustment of the blade length of each shoe. The trials were both run under a self-perceived speed by the participant which was requested to be as fast as they could feasibly achieve. In total, 7 trials of each condition were undertaken meaning for the purposes of this study, 14 runs in total were completed.

The run tests were conducted within an indoor, dry environment. The running area was segregated using tape into 3 distinct zones. There was an initial 15

metre zone used for the participant to accelerate from rest, a 4 metre zone whereby the participant was asked to ensure their best maximal (but steady state) speed, and finally another 15 metre zone used for the participant to safely slow down. These distances were defined as the maximum available within the test location. An indoor assessment took place as this reduced the impact of external factors such as changing wind strength and direction which would impede running speed. A treadmill could have been used but it was felt this did not allow for an instantaneous controllable reduction in speed that was felt necessary for someone using the technology.

The running order of each trial was to perform 7 fast of the less stiff shoe setting and then 7 fast of the shoes stiffer setting. Whilst the stiffer blade setting of the shoe was achieved by shortening the blade, this actually changed the geometry of the blade and increased the shoes total height by 55mm when unloaded. The 7 trials of the less stiff blade were followed by the 7 trials of the stiffer setting. A sequential running order was used.

The trials were filmed using a single video camera positioned opposite the steady state run zone, 20 metres away and were filmed at a frequency of 210Hz. The footage was analysed using the Quintic software as per Chapter 8.

The information of interest in this trial was the steady state speed achieved (to ensure test repeatability) the stride length and a qualitative visual examination of the shoe blade behaviour. The visual examination of the trials was undertaken by reviewing the video footage.

9.3.2 Prostheses Linearity Assessment

A case study was conducted to investigate the linearity and resultant stiffness of energy return prosthesis. An 'Elite Blade' composite energy return foot prosthesis (Chas A Blatchford & Sons Ltd, Basingstoke, UK) is used. This ESRP is shown in figure 32. This prosthesis is designed to undertake a range of activity including low speed running for a user having a mass of circa 55Kg.



Figure 32. Elite Blade prosthesis

The prosthesis is compressed using a static load. A dynamic method using cycling loading machines could also have been used but since the effect due to changing contact point was the main aim of the study, a less dynamic method was required. A Testometric strength testing machine was used for this experiment (Testometric Company Ltd, Lancashire, UK). The test prosthesis is shown in figure 32 and the test machine set up is shown in figure 33.



Figure 33. Prosthetic Blade Loading

In lieu of the fact that no formalised test exists, two different methods of prosthesis loading were undertaken in this experiment. A schematic of the two conditions is shown in figure 34.

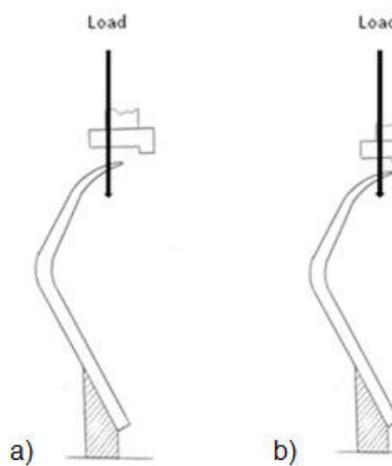


Figure 34. Testometric Loading Conditions for a) SDE and b) FDE method

a) A 28mm slide of the distal end before becoming fixed at the distal end (SDE)

b) Fixed at the distal end (FDE)

Condition 'a' demonstrates a compression of the prosthesis but the distal end is initially free to move under load. It does so for a fixed distance of 28mm after which it then locks into position and continues to be loaded. Condition 'b' demonstrates a prosthesis compressive load method whereby both the shank and the distal end are fixed. As such, this trial simulates a controlled change in length by allowing for the prosthesis to bend under load.

The prosthesis distal end of both conditions was fixed by locating against a ledge within an acetyl block as the load is applied. Ten loadings of each condition to a maximum load of 2000N were conducted. 2000N is used as this is approximately four times the bodyweight of the intended user for this prosthesis specification. Such a bodyweight impact has been suggested as being consummate of high speed running (Mero et al. 1992). The mean of each loading was recorded and the Coefficient of Variation (CV) is used to ensure statistical repeatability and stability of the process. The CV is defined as Standard Deviation divided by the mean then multiplied by 100 to reflect this ratio as a percentage. The load application rate of each loading was 50mm per minute. Mechanical stiffness was calculated as load (N) divided by deflection (mm). The stiffness's of both the peak loading and the average of the full load cycle was recorded for later comparison.

9.4 RESULTS

9.4.1 Run Tests

The summarized results showing the conditions of the trials are presented in table 17. The raw data is contained in Appendices D.1.

Table 17. Condition 1&2 Summary

	Blade Setting	Self-selected Speed	Running Speed Mean (M/s)	Mean Stride Freq. (Hz)	Stride Freq. Coefficient of Variation (%)	Mean Stride Length Difference (m)
1	Less stiff	'Fast'	4.60	2.98	7	0.05
2	More stiff	'Fast'	4.68	3.33	5	0.04

The Coefficient of Variation scores are of a low percentage especially considering the subjective nature of the running speeds by the participant. As a frame of reference, the typical step to step timing was ~0.3 seconds which is slower than the race specific typical steps of 0.2 seconds indicated in chapter 7.

The behaviour of the ESRF technology at the point of ground contact is shown in figure 35. Figure 35 demonstrates the ground contact point shifting due to running gait. In both images, point 1 indicates the initial ground contact point. The arrow in 35(a) shows the shift from heel strike to mid stance. The arrow demonstrates the mid stance distal end of the blade upward deflection. Figure 35(b) shows the ground point of contact shift from heel strike (1) to toe off (2). The arrow demonstrates the displacement of the boots ankle point from initial contact to toe off.

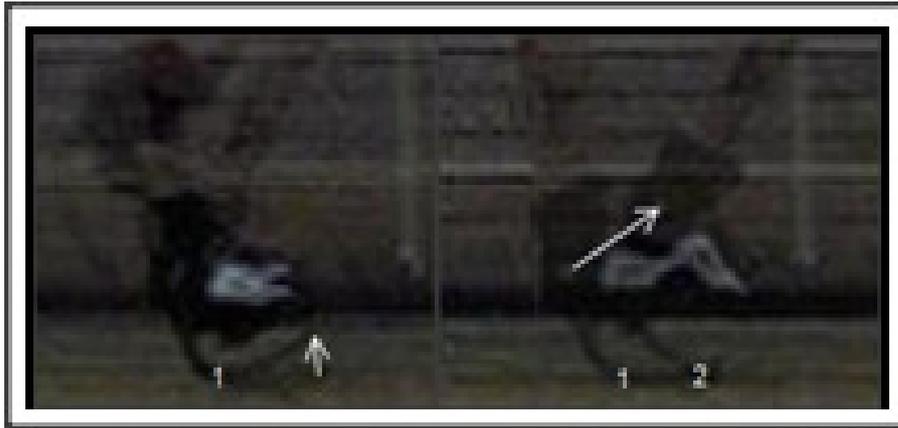


Figure 35. Heel strike to mid stance (a) & heel strike to toe off (b)

The blade contacted the ground roughly midfoot of the blade which then moved marginally to the rearfoot due to the blade bending. However, once mid stance was achieved, the point of contact begins to shift forwards until take-off. This meant that the effective spring length of the blade at the beginning of the gait cycle was quite short but then progressively lengthened towards toe-off. This demonstrates a non-linear response in stiffness from a blade of this nature when under compression. Ultimately the blades stiffness will reduce as the ground contact phase continues and potential energy is converted to kinetic energy through vertical movement of the athlete.

9.4.2 Prostheses Linearity Assessment

The results of the FDE and SDE loading conditions are shown in table 18. The graphs of the tests are contained in appendices C.2.

Table 18. Loading Method Results

Value	FDE	SDE
Mean stiffness of load cycle (N/mm)	48	42
Average stiffness of total load cycle (N/mm)	39	26
Peak stiffness from 1500N-1950N sample (N/mm)	69	76
Percentage increase of peak load stiffness over average stiffness (%)	23	61
CV of stiffness at 1950N (%)	1.1	0.2
CV of average stiffness of total load cycle (%)	1.7	0.1

The low coefficient of variation suggested extremely high levels of repeatability of the prosthesis behaviour using both the FDE and SDE methods. The SDE method had a CV of 0.1%. The SDE method had a CV of 1.7%. The obtained stiffness from the two methods does highlight a distinctive difference in measured performance. Since the deflection measured by the assessment machine will be relative, it is obvious to see a difference in the overall mean. However, there is also a difference when measuring the last 450N loading sample too.

The typical load/deflection plots of both the FDE and SDE methods can be seen in figure 36.

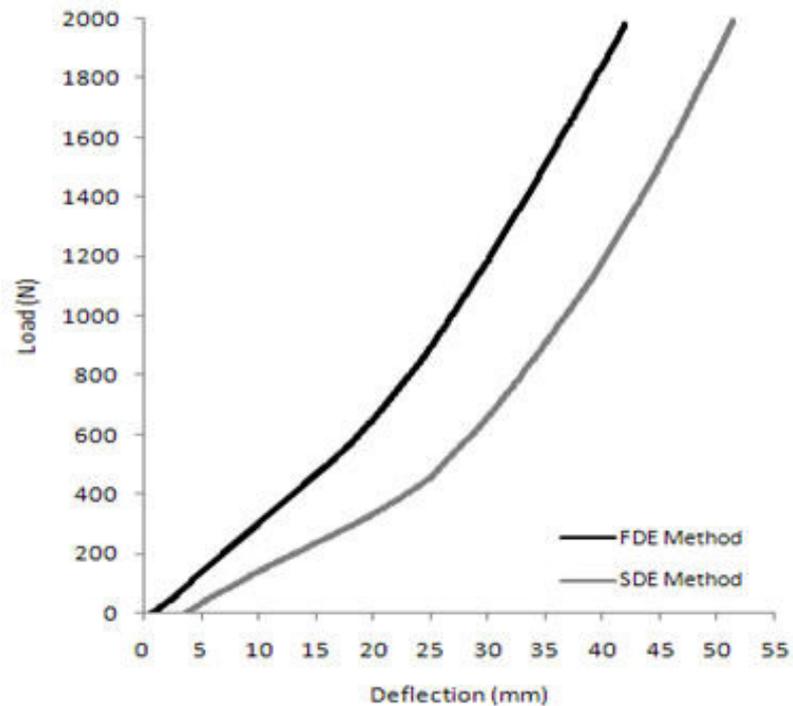


Figure 36. FDE & SDE Load/Deflection Behaviour

It was seen that allowing a slide of the distal end did create a significantly different obtained stiffness. The FDE method had a higher overall mean stiffness. The SDE method can be seen to be initially less stiff as the changing spring length is altering the load cycles boundary conditions and thus its mechanical properties.

Most importantly, from these plots it can also be seen that the prosthesis exhibited initial non-linear behaviour irrespective of which loading methods were used. The SDE method does show a decrease in stiffness caused by the controlled distal end slippage which will be due to the relative measurement of the machine. However, once engagement of the distal end takes place, a reduced, progressive non-linearity is witnessed and a near parallel trace of the two methods takes place. However, whilst it appears identical, the SDE and FDE mechanical stiffness of the upper 450N final load cycle of the graph trace still had a slight difference which was shown in table 18 to be 7N/mm.

9.5 DISCUSSION

The first research objective sought to establish the stiffness behavior of ESRP when subjected to running. The performed runs tests were undertaken under repeatable conditions. The runs produced a step frequency of around 3Hz which is less than the reported 5Hz witnessed in able-bodied 100m sprinting (Mero et al. 1992). However, such a comparable effort would have meant excessive fatigue on the part of the participant coupled with safety concerns using the shoe technology at such speed and the larger acceleration and de-acceleration zones required.

The run tests produced a fundamental change in boundary conditions due to deflection and stiffness variation of the blade due to foot roll through. This was due to the amount of clockwise rotation the blade was subjected to during the gait cycle. Further investigation is required to ascertain the magnitude of this foot roll in amputee elite athletes. However, qualitative variation in the ground contact position of bi-lateral amputee Oscar Pistorius during competitive racing is shown in figure 37.

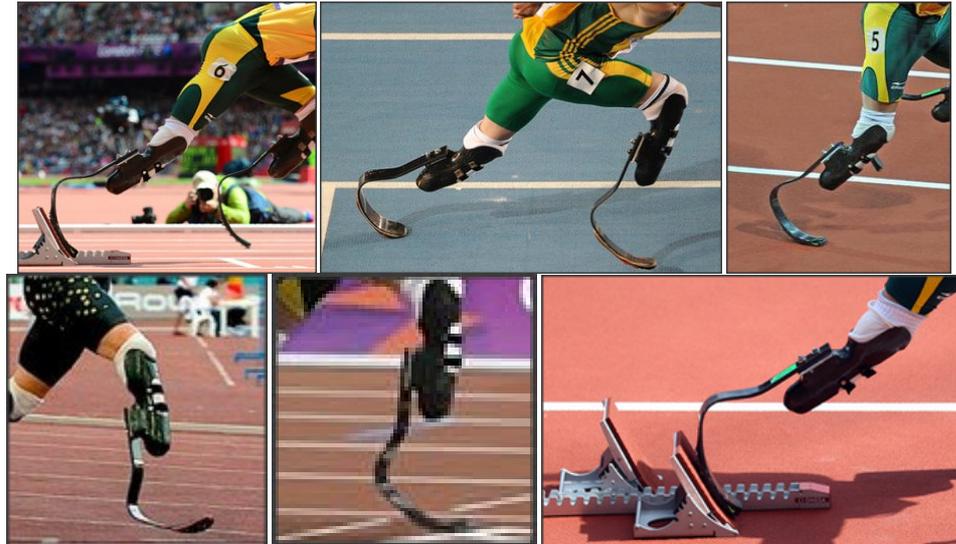


Figure 37. Oscar Pistorius Prosthesis Ground Contact Position Change.

Prosthesis foot roll is going to alter the blade length and therefore its stiffness response. This would also contribute to the second objective as this demonstrates a likely non-linearity of the technology when running.

The second objective was addressed with the static load tests. There was a difference in performance of the prosthesis depending on its length or contact point. Non-linearity was witnessed in the early stages of loading. It is proposed that this was due to the tapered profile of the 'foot' region of composite material. The magnitude and proportion of such non-linearity would likely be small and unique to each design but it should be noted that such a characteristic exists nonetheless. This supports previous claims that variable stiffness parameters could be important for running prostheses design in the future (Farley & Gonzalez 1996).

This study investigated whether the prediction of ESR technology stiffness was possible when using static load techniques. With the SDE method, the obtained bending deflection would be inaccurate due to the constantly shortening spring length of the 'toes' arching through. The 28mm slippage of

the SDE method created a 12% perceived loss in prosthetic stiffness. This was caused by a combination of the change in spring length and the relative measurement of compressed deflection of the machine. Such a characteristic makes the prediction of ESR stiffness (by then extending the linear portion) increasingly inaccurate and therefore unfair to assess or regulate the technologies response. From a clinical point of view, not ensuring the ground contact point and the point statically loaded are the same, could mean that at best, significant tuning of an athlete's prosthesis geometry would be required and at worst that an incorrect prosthesis would be fitted. Fixing at the distal end would underestimate the ESRP mechanical stiffness. If such static loading was used to prescribe or evaluate ESRP technology in the future, the lower portions of such graph traces should be disregarded and the linear-like section of a load as close to those expected in the individual's event should be selected. When this data is combined with the run tests change in the ground contact boundary conditions these experiments have highlighted that any assessment strategy of ESRP's should use more dynamic loading methods to compare lower-limbs.

9.6 CONCLUSION

ESRP technology was investigated to ascertain whether it was, as per this thesis literature review, a simple spring with linear qualities. Run tests demonstrated that the foot is subjected to constant boundary condition changes at the point of ground contact. This will change the spring length and therefore its effective stiffness.

Compression load tests of ESRP demonstrated that it can also possess non-linear behavior even when assuming the point of contact does not change. If the point of contact does change, this will further change its stiffness qualities. It is recommended that standardisation of such tests is also

recommended as fixing at the distal end is the most accurate but likely underestimates the ESRP stiffness when in use.

As a result, prescription of such technology assuming linear qualities cannot be recommended. A more dynamic method of direct limb to limb assessment is preferred.

9.7 ACKNOWLEDGEMENTS

The prosthesis used in this study was kindly donated by Chas A Blatchford & Sons Ltd. (Basingstoke, UK). Special thanks also go to both Shelley Broomfield and Andrew Callaway for their assistance with the data collection of the run test experiments undertaken in this chapter.

**CHAPTER 10: A PROPOSAL FOR AN
ASSESSMENT STRATEGY OF LOWER-LIMB
RUNNING PROSTHESIS - A CASE STUDY**

10.1 INTRODUCTION

Chapter 6 proposed guidelines to regulate the performance of a running prosthesis. It encouraged prostheses to be judged as a form of sports equipment. However, it also was shown in Chapter 9 that such technology has a non-linear stiffness. As a result, it was recommended that the prosthesis should be attached to its user and assessed dynamically when judging its performance. This aside, Chapter 6 also recommended using techniques that would provide direct limb to limb comparison. With this in mind, this chapter proposed an assessment method for the regulation of lower-limb running prostheses. This chapters study has seen peer review via journal publication (Dyer et al. 2012) and is contained within Appendices F.

10.2 OBJECTIVES

The objectives for the proposed assessment technique are:

- a. To investigate the *repeatability* of a functional lower-limb assessment.
- b. To investigate the *symmetry* of a functional lower-limb assessment.
- c. To recommend approaches to further develop the proposed assessment strategy in the future.

10.3 METHODS

A functional method which has been shown to have metrics that correlate with running performance is proposed as a less demanding assessment method than running. This chapter investigates the feasibility of using *jump testing* as a need to regulate lower-limb running prosthesis (Chapter 5 & 6) by investigating the qualities identified in this thesis as *stiffness* (Chapter 2 &

9), *limb symmetry* (Chapter 2 & 7) and *energy return* (Chapters 3 & 6). Jump testing is used as the proposed method to assess uni-lateral amputees. Whilst run testing has been performed by amputees on treadmills, jump tests have been correlated to sprint performance (Holm et al. 2008), can provide independent leg assessment (Strike & Taylor 2004) and provide a 'float phase' i.e. with neither feet touching the ground, as per running (Umberto et al. 2006).

The limitations of any proposed assessment strategy was that due to the non-linear stiffness of a lower-limb, Chapter 9 recommended a method which was as context specific as possible. However, it is not realistic to expect an athlete to perform a maximal, race pace effort of an event like the 100m, 200m or 400m reliably. In addition, this would not be realistic as only one run could be feasibly realistic yet statistical robustness would ideally demand several runs. Therefore, a jump test was proposed as a dynamic method which could produce race specific ground impacts which would allow the lower-limb to respond accordingly. In addition, aspects such as test induced limb fatigue were alluded to in Chapter's 9 and 10 but this had also not been investigated yet in this thesis.

10.3.1 Drop Jumping

To potentially obtain the ability to measure the ability to monitor the limb to limb symmetry of the lower limbs of the amputee runner, a uni-lateral drop jump is proposed as a solution. The test is specified as a uni-lateral (rather than a bi-lateral) drop jump as this will allow the left and right legs to be separately evaluated and then compared when subjected to pre load and propulsive forces (Stalboom et al. 2007). The load upon the limb is provided by a freefall phase of the drop rather than the athlete's efforts. This minimises the ability to 'cheat' the test.

The bi-lateral or uni-lateral drop jump test is typically undertaken by having a participant stand on a platform of a given height above the ground. Once commenced, the participant jumps down to the floor landing on either one or (more typically) two feet and then immediately executes a vertical or horizontal jump on the same foot/feet (depending on the technique method chosen). The achieved displacement is then measured as the magnitude of muscular power. The height of the jump creates the running events expected magnitude of ground impact (thereby generating context specific lower-limb stiffness response). The landing phase could be used to calculate lower-limb stiffness. The launch phase can then be used to form the basis of energy generation limb to limb comparison. The advantage of this technique is that it uses a manipulation of drop height and the person's weight to provide a ground impact to create the lower-limbs appropriate stiffness response, as opposed to the athlete's effort. Alternatively, by standardising the participant's weight, drop height and impact of gravity means, that the potential energy can be quantified and standardised (in Joules) using this technique. An additional advantage is that the secondary, vertical launch phase can assess the energy return of the overall limb although it was conceded that due to the passive nature of the current acceptable level of technology, this may not be currently relevant.

Drop jumps are typically used as a form of dynamic training to improve jumping performance (Bobbert et al. 1987a), as a form of strength training (Wang 2008), plyometric training which involves eccentric muscular contraction (Baca 1999), or for sprint training to improve the horizontal impulse (Holm et al. 2008). The jumping phase is an indicator of lower-limb power. It has additionally been used to ascertain the stiffness in the limbs upon landing (Devita & Skelly 1992). Lower-limb stiffness has been calculated through application of the spring mass model (Wang 2008; Cavagna 1964) and with a ratio of peak vertical force and maximum change in length between two fixed points (McGowan et al. 2012) or using a sine wave method (Morin et al. 2005). The drop jump is used either as a training method to *improve* the physical ability of jumping or is used as a diagnostic

assessment to *measure* jumping strength. In this case, a uni-lateral drop jump would allow the performance of a prosthesis to be compared and limited by the naturally generated performance of the athlete's biological limb.

The impacts of drop height used for this method (and its effects) have also been investigated. Several studies with able-bodied participants have used comparatively low heights of 20cm (Baca 1999; Bobbert et al. 1987a), 12 inches (Noyes et al. 2005), 30cm (Barber-Westin et al. 2006), 31cm (Earl et al. 2007), medium sized drops of 39cm (Baca 1999), 40cm (Bobbert et al. 1987a) and large heights such as 45cm (Ambegaonkar et al. 2005), 60cm (Bobbert et al. 1987a) and 80cm (Viitasalo et al. 1998). Several comparative studies of varying heights have been investigated (Viitasalo et al. 1998; Bobbert et al. 1987a) to determine the optimum height but validity has been established for heights as low as 20cm (Bobbert et al. 1987a).

The technique when performing the drop jump has been suggested to be tightly controlled (Bobbert et al. 1987b) although prior familiarisation or training of the drop jump technique has also been suggested as not being required to obtain test reliability (Laffaye et al. 2006).

Within sport science, the drop jump has been performed by sports performers. These have included physically active individuals, (Stalboom et al. 2007; Schot et al. 1994; Bobbert et al. 1987a) adolescent athletes (Barber-Westin et al. 2006), elite level biathletes (Krol & Mynarski 2012), Norwegian national level triple jumpers (Viitasalo et al. 1998), basketball and hockey players (Rishiraj et al. 2012), volleyball players (Bobbert et al. 1987b) and men from team sports (Baca 1999).

Several studies have attempted to identify the correlation between sprinting ability and jump testing performance using able-bodied participants to ascertain its ability as a diagnostic or talent identification test. Some studies have shown a direct correlation with bi-lateral jump testing and short distance sprinting (Maulder & Cronin 2005) however; this has been disputed (Kukoli et al. 1999). However, these two studies both agree that vertical jump displacement and sprinting performance correlate significantly. Additionally further work using several dynamic jump methods has shown improved correlation within different phases of the 100m sprint using different jump methods (Bret et al. 2002) or similarly different leg strength qualities (Maulder & Cronin 2005). A single leg horizontal drop jump has been shown to be highly related to sprinting (Holm et al. 2008) with the observation that (whilst not often used), horizontally performed jumps are better predictors of sprint performance (Maulder & Cronin 2005). However, it is not known at this time any issues regarding test subject safety when performing horizontal jumps within a clinical setting as opposed to vertical jumps which alternatively use a smaller footprint and less forward momentum of the amputee which still demonstrate qualities representative of sprinting (Maulder & Cronin 2005; Kukoli et al. 1999). As a result, dynamic leg power assessment methods such as the drop jump have been shown to be applicable to sprinting but their selection may relate to a particular phase within short distance sprinting with increasing/decreasing correlation.

Little evidence has been seen of drop jump use when performed directly on lower-limb amputees. Lower-limb amputees have however performed other jump test variants such as *uni-lateral vertical jumping* (Strike & Diss 2005) and a *one-foot vertical jump with approach* with uni-lateral trans-tibial amputees (Strike & Taylor 2004). In the 2004 study, the maximum height and flight time were reduced noticeably on the prosthetic side but this study's findings should be taken with a degree of caution as it was only performed with two participants. No studies of *athletes with a lower-limb amputation* performing uni-lateral or bi-lateral drop jumps are currently evident within the literature. This also means that any differences in lower-limb damping

between an artificial sprung prosthesis and the natural spring characteristics of a biological leg have also not been investigated.

A single leg drop jump is a relatively recent variation of the drop jump method. A horizontal variant of the uni-lateral drop jump has been shown to be reliable (Stalboom et al. 2007). Whilst a relatively recent development, the uni-lateral drop jump has been performed to determine kinematic and kinetic joint differences (Weinhandl et al. 2011), ankle joint instability (Delahunt et al. 2006), differences in sex (Russell et al. 2006). The heights used to perform this jump have included 20cm (Weinhandl et al. 2011; Stalboom et al. 2007), 35cm (Delahunt et al. 2006), 60cm (Russell et al. 2006). The minimum height of 20cm has been used as this has been shown to be a height that untrained participants could still be accustomed to undertaking (Stalboom et al. 2007).

Drop jumping in practise does have several concerns as to its use. The magnitude of the height used has been cited as modifying the technique used to perform it (Bobbert et al. 1987a), likewise upper-limb motion has been shown to affect the generated impulse (Laffaye et al. 2006) meaning arm motion to stabilise height or create comfort to the participant of the dropping height would have to be removed. If this is not controlled, the effect of the arms may influence the results affecting its correlation to sprinting. It has also been suggested that to increase the jump height up to 60cm creates net joint reaction forces with sharp peaks (Bobbert et al. 1987a), as well as observations of an altered jump technique performed by the participants (Viitasalo et al. 1998). It has been proposed that there is a potential for injury in the ankle if 10 or more jumps are performed (Delahunt et al. 2006) and that fatigue will lead to changes in movement patterns in the lower-limbs (Weinhandl et al. 2011). These observations may be less desirable or raise ethical issues. However, in terms of test competence, it should be noted that athletes with a lower limb amputation already performed the long jump event at the 2008 Paralympic Games (www.paralympic.org/Sport/Results/) and empirical assessment of jumping events have taken place (Nolan et al. 2012; Nolan & Lees 2007; Nolan & Lees 2000). The problems may not be linked to

competence to complete the technique itself but merely the methodology of the experiment undertaken. Finally, the technique may not be used as a means to easily compare above-knee to below-knee amputees directly. Since trans-tibial amputees still have the use of their knees, it is likely that the lower limb knee (rather than the prosthesis) will damp the drop jumps ground impact due to their leg bending. However, a trans-femoral amputee does not have a knee therefore they may use other compensatory strategies - thereby changing the tests boundary conditions.

Ideally, the height for the drop jump should be optimised through testing to create a lower-limb stiffness response applicable to the athletes running event – for example, a 400m runner would see less stiffness and therefore drop from a lower height than the 100m sprinter equivalent. However, at this stage, this case study investigates the basic feasibility of the technique when dealing with highly asymmetrical lower-limb functionality. Optimisation of the drop height will not be considered in this case study.

10.4 TEST PROTOCOL

Ethical approval for the pilot test was formally registered and approved by the author's research institution. A single male able-bodied candidate with a background in international level sport acted undertook these pilot tests and was the same candidate as the one used in Chapter 9. The test candidate was male, 195cm tall and had a mass of 90kg.

The protocol of the drop jump was to stand on the intended landing leg on top of a 20cm high platform. The lowest height would be used for reasons of safety and this height had been indicated within the literature review as the lowest that had achieved reliable results (Bobbert et al. 1987a). With a standardised height, mass of participant and impact of gravity, the potential

energy would be mass x gravity x height therefore being 176.58 Joules for each drop to first impact.

When ready, the drop down action were performed, landing in the centre of the pressure pad and then, using the same take off leg, immediately execute a maximal effort single leg vertical jump. The jump procedure is concluded by landing on both feet. Any required 'run off' for the participant after the jump was performed was allowed. There was a 1 minute timed break between each jump being performed. The left and right feet were alternated and 12 jumps on each leg were performed. Any changes in performance over the course of the jump testing were assessed by comparing jumps 1-6 and 7-12. Due to the case study approach, the impact of the designed lower-limb asymmetry and to minimise any safety concerns, the lowest recorded reliable drop jump was used as reported Bobbert et al. (1987a).

A RS Footscan pressure pad, (RSscan Ltd, Ipswich, UK) sampling data at 253Hz was used to record the mean ground reaction force data of the drop jumps first and second contact phases and the duration from the first to final landing. Force data was used in this pilot study so as to easily measure a metric from both landing and takeoff. The pad was used as it was conceptualised that this test would be performed quickly at a major sporting event and that this method was fast and simpler to set up than many other measurement tools. Ground reaction force is relevant to sprinting performance as promoted by Weyand et al. (2000). The Footscan's accuracy was checked beforehand by calibrating using known masses. In addition, the symmetry index (SI) of both limbs was used as described by Barber et al. (1990) as: *Non dominant leg/dominant leg x100*.

Due to the test subject not using a running prosthesis, the subject's limb to limb performance difference was created through use of footwear on one limb. The participants left foot was bare (dominant) whereas the right foot

was shod (non-dominant) using new and previously unused sports footwear. This was undertaken to help provide a greater difference in the mechanical behaviour between the left and right feet that overcomes a typical limb asymmetry such as those indicated by Sadeghi et al. (2000) and limb to limb symmetry indices differences observed from several jump test experiments by Maulder and Cronin of a 4-11% range (Maulder & Cronin 2005). It was conceded that use of the footwear on one side would increase the drop height by a small fraction but the magnitude of the force data was not being assessed in this pilot. Alternatively knee braces have been used to create lower-limb imbalances (Rishiraj et al. 2012). This technique was rejected since it was felt that even a below-knee amputee often still retains the use of their knee and that the strapping and adoption of a knee brace could not be fitted from trial to trial reliably or repeatedly.

The mean and standard deviation is used to calculate the coefficient of variation (CV) of the results. The CV has been defined as a measure of absolute consistency when evaluating a series of results (Stalboom et al. 2007) and is calculated as $SD/Mean*100$.

10.5 RESULTS

The raw data of the drop jump test is contained in Appendices E.1.

The coefficient of variation (CV) in ground reaction force (GRF) of the full landing to landing phase across the 12 unilateral drop jumps was 6% (left side barefoot) and 8% (right side shod). The coefficient of variation of the duration of the first to second landing of the 12 unilateral drop jumps was 5% (left side barefoot) and 11% (right side shod). The Pearson Coefficient Correlation (PCC) is used as a measure of the strength of the association

between two variables. This is defined by Rodgers and Nicewander (1988) as:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

The PCC between the left and right side average force outputs was 0.12 indicating a low relationship of the two data sets.

The Symmetry Index (SI) was calculated as per chapter 8. The SI of the average GRF of the full landing to landing phase was a 29% impairment to the side that was shod.

To check how the jump performance changed over the series of drop jumps, the 12 jump set was also split into jumps 1-6 and jumps 7-12. In this case, the mean GRF created by the left foot (bare) saw a CV of 6% (jumps 1-6) and 7% (jumps 7-12). The mean GRF created by the right foot (shod) saw a CV of 3% (jumps 1-6) and 8% (jumps 7-12). The SI impairment on the shod side was 32% from jumps 1-6 and 26% from jumps 7-12.

The first landing to second landing time duration from the left foot (bare) saw a CV of 2% (jumps 1-6) to 7% (jumps 7-12). The first landing to second landing time duration from the right foot (shod) saw a CV of 11% (jumps 1-6) to 12% (jumps 7-12).

10.6 DISCUSSION

This chapter had three core objectives. The first was to investigate the *repeatability* of lower-limb landing and launch forces when performing the uni-lateral drop jump. A pilot test of the uni-lateral drop jump was undertaken to assess the statistical viability of the technique. From 12 jumps, there was a marked difference in mean jump GRF behaviour between jumps 1-6 and 7-12 in both feet. For the left bare foot, jumps 1-6 saw a relatively minor GRF CV increase of 6% to 7% from jumps 7-12. Such values of variance are typical of ground reaction forces in reliability studies of the uni-lateral drop jump when using able-bodied participation (Stalbolm et al. 2007). However the right shod side saw a marginally larger change of CV from jumps 1-6 and 7-12 in GRF data of 3% to 8%. This increase still maintains a desirable level of CV but does indicate a marked increase in variance of the data as the test jumps increase. It is possible that use of the footwear created some degree of fatigue and/or jump technique degradation on the shod side as the series of jumps continues. Such an effect could be evident when assessing an amputee's biological limb compared to their prosthesis.

The duration of the jump being performed from drop landing to final landing saw CV's from the left bare foot of 2% (jumps 1-6) and 7% (jumps 7-12) whereas the right shod side saw 11% (jumps 1-6) and 12% (jumps 7-12). This larger variability in the behaviour of the footwear continues the theme of either fatigue and/or jump technique degradation. However, the mean average of landing to landing jump duration over jumps 1-6 and 7-12 are virtually identical suggesting that limb fatigue per se' may or may not be the cause but that some kind of technique change occurred over the length of the test. Like the GRF data, this shows greater variability after 6 jumps. On this basis, it is proposed that the technique is reliable and repeatable but that the number of jumps in future trials needs to be as few as possible to maintain good technique. It needs to be ascertained whether this degradation in an impaired limb is also seen when using an energy return

prostheses. Motion capture assessment of the joints, limbs and overall kinematics could go some way to identify this as well as more detailed investigations into energy generation and consumption using an amputee participants.

The chapter's second objective was to investigate the *symmetry* of lower-limb landing and launch forces when performing the uni-lateral drop jump. The Pearson Coefficient Correlation between the left and right side average force output data sets was 0.12 and is very low. It could be speculated that one side will fatigue at a different rate to the other and therefore potentially behave very differently. The fact that the CV of the right hand side was much greater than the left coupled with both the symmetry index indicating a 29% (across all 12 jumps) and the mean durations being similar across both halves of the trials suggests the shoe acted as a major impairment and behaved much more erratically in continued use. Whilst no SI data has been identified historically for when performing the unilateral drop jump technique, the SI score of 29% in this study is considerably higher than an 11% range recorded when performing a vertical squat jump with able bodied subjects (Maulder & Cronin 2005). This demonstrates a consistent limb to limb performance significant impairment and therefore satisfies the second objective.

The studies final objective was to determine whether this technique should be recommended for use in the future. The greater erratic performance of the shod side after 6 jumps suggests that whilst mean performances are stable, the number of jumps should be kept fewer than 6 if performance repeatability is the goal. This raises an interesting point about the evaluation of mixed limb performances. The SI between the two limbs when the limbs are fresh compared to when the limbs are fatiguing towards the end of a 100m sprint could be very different. As a result, this pilot study raises the philosophical question of not only viability of this evaluative technique but also at which prior state of limb fatigue are compared as both are part of the nature of the

100m sprint race. This fatigue profile and SI will vary when based upon Nolan's observations that prostheses designs behave very differently (Nolan 2008). As such, the technique is recommended but that further investigation is required into the impact of fatigue as well as philosophically how this should be accounted for when creating a context specific assessment of LLP. The stiffness of the lower-limbs was not calculated in this study to ascertain if a 20cm drop provoked a response typical of that experienced by the limb in running events such as the 100m. This was because the emphasis was placed on using force to determine the techniques repeatability whilst maintaining the best possible safety to the candidate rather than to optimise the drop height. Further studies are required to determine what height based on body weight provokes the same stiffness response as those found at a specific events running speed.

As a final observation, concerns could be raised that athletes could cheat by purposely underperforming the drop jump test when in actual use. Whilst the final vertical phase could be manipulated, the initial drop is governed by the athletes mass, gravity and the height of the drop and therefore could not be underperformed. As a result, the calculated limb stiffness could not be cheated. If limb power from the vertical phase were intentionally underperformed, it is plausible that several successive jumps would likely highlight an erratic behaviour and thus signify potential cheating. Ongoing competition to competition testing would likely build up a long term performance profile of the athlete to monitor this.

In summary, no concerns were raised in the pilot testing that suggests this technique is not a viable solution for the evaluation of sprint athletes with unilateral lower-limb amputations. This technique is recommended for further development by assessing a larger test subject group of athletes with a lower-limb amputation with greater lower-limb asymmetries.

10.8 CONCLUSION

This chapter conceptualised use of a uni-lateral drop jump technique as a realistic means to monitor limb to limb symmetry of lower-limb stiffness.

This case study of the uni-lateral drop jump noted that the number of jumps executed should be less than 6 and that limb to limb symmetry drifts once the number of jumps is increased. The characteristics of limb-to-limb performance and the rate and type of fatigue is an observation recommended for further study with athletes with an amputation. Provided the number of jumps is kept low, this technique is felt to be a valid method for this application but that further investigation is required to optimise its use as an assessment tool.

10.7 RECOMMENDATIONS

The uni-lateral drop jump technique should now be developed by using a range of amputee athletes to further prove its reliability. Additionally, the best measurement method to measure the jump metrics such as energy return or lower-limb stiffness should be established. Alternatively, standardised test metrics such as potential energy could be used to normalise the tests for different athletes or race distances (based upon varying the drop height). The pressure plate could be substituted by use of motion capture technology or sensors such as accelerometers. Ideally, a highly portable, quick to set up and cost effective solution should be sought out. The drop height in this study was established when reviewing the current literature of the technique coupled with the unique needs of amputees. However, it should be investigated if a calculated drop height (based upon the participant's bodyweight) that would represent the ground impact of an individual's

athletes chosen event is feasible so as to increase the specificity of the test with the intended context in mind.

Whilst the uni-lateral drop jump technique itself is proposed here as robust, the role and impact of lower-limb fatigue is also worthy of further study. Accepting that a prosthetic limb cannot fatigue but that the biological limb can, the limb to limb symmetry indices change might prove useful when discussing the regulation of such technology philosophically. For example, at the start of a 100m event the athlete's lower-limbs will not be fatigued. However, once the event is underway, the limb to limb symmetry ratio of ground reaction force will change as the biological limb fatigues. What is not known is whether this effect should be accounted for when designing regulation strategies for lower-limb prosthesis technology. Fatigue when performing the bi-lateral drop jump has been identified (Skurvydas et al. 2011) but with athletes. A 'fatigue index' may be more applicable to limb to limb behaviour in a race rather than assuming such a relationship is static.

CHAPTER 11: CONCLUSIONS & RECOMMENDATIONS

11.1 SUMMARY

A literature review, documented in Chapters 1 and 2, revealed the sports background relatively recent introduction and that it was currently stable in both its racing formats and expectations. It was also revealed that research (specifically those regarding athletes with lower-limb amputations) were little more than 14 years old and saw low participant numbers due to the limited number of athletes being available.

A literature review was performed in Chapter 3 that sought to investigate what issues occur when technology is used in sport and what cases of controversy had occurred before. It was shown that cases had occurred in able-bodied sport frequently plus that some athletes with a disability within able-bodied sport had been the source of controversy. As a result, it was concluded that there was no reason why disability sport specifically would not suffer the same controversies.

Chapter 4 proposed a mixed method research approach as this would allow the investigation of philosophical issues but would also provide pragmatic outcomes that could be recommended as practical guidance to the sport.

Chapter 5 attempted to address the first objective of this project research by investigating the impact of any prostheses technological change that has occurred in the sport and to ascertain whether any regulation on their acceptability would be of value in the future. It undertook a performance improvement statistical evaluation. This proposed that technological change can create changes that may not be of value to the sport and can create negative ones such as decreased participation levels. It also demonstrated improvements in the sport, well in excess of the able-bodied equivalent. This information proposed that historical changes in technology were not of value

but that any further changes in the future would require a proactive review prior to adoption. Crucially, it was concluded that acceptability guidelines were necessary as part of amputee running in disability sport.

Chapter 6 investigated two further objectives of the research project. These were illustrating the current perceptions of lower-limb running prosthesis used in competitive disability sport and to propose guidelines for LLP technology inclusion when used in competitive running with a lower-limb amputation. The chapter undertook a stakeholder review by using the Delphi Technique to obtain consensus on the perception and role prosthetics technology played in disability sport. A three round process proposed a series of consensual guidelines. These guidelines were descriptive and not fully prescriptive. Some guidelines were stated to require further clarification upon which to propose any form of assessment. The guidelines requested that running prosthesis were, as a maximum, restorative forms of equipment in terms of both stride characteristics and mechanical contribution. Crucially, it confirmed the proposal in Chapter 5 that such technology should be regulated through assessment methods.

Whilst Chapter 6 advocated restorative step characteristics to the amputee, the literature demonstrated that the nature of step behaviour in an actual racing environment was not currently known. This was investigated in Chapter 7. A video analysis revealed that a low step count was desirable for success but crucially that limb to limb asymmetry, much larger than those reported in previous studies, took place in 100m racing. The reasons for this could not always be given. As a result it confirmed that inter-limb comparison should be included as a quality in the acceptability guidelines but that also that limb to limb symmetry should be included as a metric within any proposed assessment strategy.

Chapter 8 sought to explore an issue created as a result of the Delphi study in Chapter 6. Chapter 6 proposed that a prosthetic limb should be of no greater performance than a biological limb. With uni-lateral amputees this is a straightforward comparison but it could not be easily seen how this could be achieved with bi-lateral amputees – especially those with congenital origination of their limb loss. Bi-lateral amputees simply have no reference data. It was decided that if functional differences could be established between them, then an argument would be made to separate the racing styles. This would not totally resolve the issue but it would allow both uni-lateral and bi-lateral amputees to be taken on their own merits and likely warrant their own separate assessment strategies. A case study was undertaken which standardised the participant but varied the limb to limb mechanical performance symmetry. It was demonstrated that the participant was forced to vary their limb speed to maintain symmetry of lower limb mechanical function. It was proposed that extra metabolic energy would have to be expended by the participant to accelerate their limb downstroke to do so which the symmetrical lower-limb would not have to do. It was suggested that this would need to be validated through assessment of amputees however, this study proposed that functional differences would exist as a result of the prosthesis technology and that the T43 and T44 classes should therefore be separated when racing. At this point, this thesis focused on the provision of an assessment strategy for lower-limb uni-lateral amputees only.

Chapter 9 investigated conflicting claims in the literature review whether lower-limb running prosthesis were linear-like springs. If this was proven to be the case, any proposed assessment strategy could have been non-invasive and easier to implement. Unfortunately, both run tests and compression loading tests demonstrated that in actual use, LLRP's have non-linear stiffness due to both footroll and a changing point of ground contact. Due to their construction, it was also shown that further non-linearity existed and that therefore prediction of their behaviour was not possible. It was recommended that any assessment strategy should be dynamic in nature and allow direct limb to limb comparison.

The final chapter proposed a suitable concept of assessing athletes with a uni-lateral amputation's based upon the need established in Chapter 5, the criteria of Chapter 6 and the further investigations of Chapters 7, 8 and 9. A drop jump test method was proposed and pilot tested. This method would allow a reliable assessment of lower-limb stiffness and the limb to limb symmetry. Should the technology be allowed to further develop in the future, this technique would also be able to assess the passivity of prosthetics technology by being able to assess energy return if required. The technique can be conducted within a restricted environment and could be developed to investigate elements such as limb to limb fatigue and allow for variation in different drop heights or potential energy to specifically replicate the limb impact of different events.

11.2 CONTRIBUTIONS TO KNOWLEDGE

The research question for this thesis was:

“What is an acceptable use of lower-limb prostheses in short distance running at the Paralympic Games and how should such technology be assessed?”

This research has four key contributions that directly address this question:

1. It established a need for prostheses technology acceptability guidelines and assessment in lower-limb amputee competitive running. This discovered need was new knowledge in the context of running with an amputation competition.

2. It produced a set of guidelines that define the role and perception of lower-limb running prosthesis in current competitive running with an amputation. These guidelines are offered as new knowledge in this context.
3. It proposed that the athlete amputee runner population should race separately in their T43 and T44 classifications. Whilst the classification of amputee athletes has evolved over the last 35 years, this novel finding provides guidance as to the structure of amputee competition in the future.
4. It pilot tested a concept dynamic assessment method which can assess the limb to limb performance properties of an athlete with a uni-lateral lower-limb amputation. This is a new application of an existing technique but in a novel context.

11.3 EVALUATION OF OVERALL RESEARCH METHOD

This project adopted a mixed method approach when resolving the key aims and objectives of the research question. This proved a successful as its experience fell in line with Chapter 4's literature review of the technique. For example, it made it possible to provide practical and pragmatic solutions to the contextual research problem rather than relying on just qualitative or quantitative methods alone which would have had limitations in their direct impact to the sport.

However, it was noted in Chapter 4 that one of its drawbacks was that bias could occur based on the nature or background of the researcher. The author's educational background was of a mixed art and science nature so it was felt that this issue did not knowingly occur here. However, it is worth noting that when journal publication was sought throughout this research

project, it seemed apparent that it was more difficult to find suitable destinations to publish. Journal reviewers would often be solely qualitative or quantitative based in background and some proposals were commented that they contained content that was unnecessary or out of scope with the targeted journal. Researchers should be prepared to defend mixed methods approaches from all research quarters.

The real value of the *parallel* mixed method approach was the responsive and relatively blank canvas it provided to investigate key themes as unexpected findings were presented. For example, the Delphi study in Chapter 6 provided several different findings that could still be seen as ambiguous by other reviewers of this research. The use of several case studies such or experiments such as those in Chapters 7, 8 and 9 allowed the further clarification of these to provide greater and more solid insight into the overarching research question.

11.4 LIMITATIONS OF OVERALL STUDY

There are several limitations of the overall research project:

1. The proposed uni-lateral drop jump test has not been validated using amputee subjects. For reasons already expressed in the literature review, test subjects have limited availability. Use of these candidates would further validate the technique but a reliable sample was not possible to locate easily when it was considered that the number of elite amputee sprinters within the UK currently numbered no greater than three.

2. This research project is very much a 'snapshot in time'. The historical data in Chapter 5, the Delphi process in Chapter 6 and the stride analysis data in

Chapter 7 could all evolve as the athlete participants would increase or change over time. However, the recommendation is that all technology in the future should be evaluated by a governing body prior to its introduction in competitive sport. This would minimise any major issues until further information was supplied on new innovations.

3. The final concept proposal of the drop jump test as a means to regulate LLRP's excluded bi-lateral amputees. Chapter 7 proposed that they should be separated and this thesis does not address how they should be evaluated as a class. It is felt that further research into the hypothetical prediction of their lower-limbs performance would be required to address this.

11.5 OVERALL RECOMMENDATIONS

Due to the broad nature of this thesis and some of the insight obtained in the course of this project, several areas of this research are considered worthy of further study.

1. A stakeholder evaluation should be extended to consider the impact of lower-limb fatigue, the differences between specific events and to determine exactly how passive prostheses technology should remain in the future.

2. The impact of specific elements with sprint running such as running round a bend, the starting blocks and changes in race speeds should be considered when functionally evaluating lower-limb amputees.

3. The dynamic elastic response timed to impulse synchronisation mentioned in Chapter 7 should be investigated as to whether it truly exists in both/either

uni-lateral and bi-lateral amputees. This may provide further evidence into their racing classification separation.

4. The relationship of functional lower-limb to limb performance over longer durations should be investigated.

11.6 FINAL STATEMENT

When this project was started in November 2007, the literature review revealed not only a relative infancy of research regarding athletes with a lower-limb amputation but that nobody had really considered or was concerned about the acceptability of prosthetics technology used in competitions like the Paralympic Games. From purely a personal perspective, when the Paralympic Games occurred in September 2012 (and towards the end of this project), the requirements for this projects aims was ultimately showcased when complaints were made by athletes over technological unfairness between their prostheses. There were further calls made later in the games for the separation between single and double amputees in sprint running at the Paralympic Games. It was not clear at the projects inception whether the findings of the study would be of practical value outside of the PhD process as the research might have led to a negative conclusion requiring no impact in current practise. Not only did this not prove to be the case but the research provided several positive experiences well beyond that of this PhD's remit. As a result, the research documented in this thesis will continue in the future, past this thesis' borders.

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APPENDICES