Characterisation of running specific prostheses and its effect on sprinting performance

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Summary

The development of the running specific prosthetic (RSP) has allowed athletes with lower limb amputations to participate at a high level in sports such as sprinting. Literature regarding mechanical properties of RSPs and their influence on the athlete's performance, on the other hand, is limited. This makes prosthetic selection a difficult task. The aim of this study was to assess the biomechanical and physiological effects of the mechanical characteristics of different RSPs on an athlete's sprinting performance.

The sprint performances of athletes with lower limb amputations were described in a retrospective analysis of Olympic and Paralympic times between 1992 and 2012, in an attempt to assess whether the technological advances in RSPs is evident. A 14 – 26% performance improvement was found for the T42 and T44 classes of the 100 and 200 m during this time in comparison to 2.2 – 2.8% for the Olympic athlete performances. These results were further supported by the lower competition density found in the amputee groups (Olympic 23.90 and 9.29 competitors.s^{-1}; T42 4.53 and 1.93 competitors.s^{-1}). It was therefore proposed that technology played a significant role in the performance progression of these athletes over the last 20 years.

Differences in the characteristics of two RSP models (model E and X) were investigated. This was achieved by athlete independent mechanical testing during which the RSPs were dropped from a height of 30 cm and left to bounce on a force platform. The results revealed differences in the peak ground reaction force (GRF_{peak}) (model E > model X; $p < 0.05$) and maximal RSP compression (ΔL) (model X > model E; $p < 0.05$). This indicated that the RSP model E is more stiffness than the model X.

These stiffness characteristics related to discrepancies in sprinting economy of an athlete completing four maximal anaerobic running tests (MART) using different RSPs. Two RSP stiffness categories of each model (E_{cat4}, E_{cat6}, X_{cat4}, X_{cat6}) were used for this testing and was randomly allocated to each testing session. It was found that the running speed at which the athlete attained a blood lactate concentration of 10 mmol.l^{-1} was the highest with the stiffest RSP (E_{cat6}), whereas it was the lowest in the softest RSP (X_{cat4}). Accordingly the lowest functional muscular fatigue as measured by a decrease in the pre and post-test counter movement jump height was found in this condition (E_{cat6} 7.35% vs. X_{cat4} 24.43%).

From these investigations it was clear that technology is an important factor in the performances of amputee sprint athletes. Therefore prosthetic selection is of the utmost importance. Differences in the mechanical characteristics of the RSPs influence the sprint physiology and biomechanics and should therefore be taken into consideration when selecting a RSP.

Opsomming

Die ontwikkeling van hardloop-spesifieke prostese (In Engels, running specific prosthetic, RSP) laat atlete met onderste ledemaat amputasies toe om op ‘n hoë vlak aan sportsoorte soos naellope deel te neem. Slegs beperkte literatuur aangaande die meganiese eienskappe van RSPs en die invloed daarvan op prestasie is beskikbaar. Die doel van die studie was om die effek van verskillende meganiese eienskappe op die biomeganiese en fisiologiese prestasie van ‘n atleet te evalueer.

In ‘n retrospektiewe analise van die Olimpiese en Paralimpiese resultate in die 100 en 200 m tussen 1992 en 2012 is die invloed van tegnologiese vooruitgang op atlete met onderste ledemaat amputasies ondersoek. ‘n Prestasie verbetering van tussen 14 en 26% vir die 100 en 200 m van T42 en T44 atlete is gevind. In vergelyking hiermee het die Olimpiese prestasie met slegs 2.2 – 2.8% verbeter. Hierdie bevinding word verder gestaaf deur die laer kompetisie digtheid in die geamputeerde groepe (Olimpies 23.90 en 9.29 deelnemers.s^{-1}; T42 4.53 en 1.93 deelnemers.s^{-1}). Gevolglik kan dit afgelei word dat tegnologie ‘n betekenisvolle uitwerking op die prestasie verbetering van hierdie atlete het.

Ondersoek is verder ingestel op die verskillende karaktereienskappe van twee RSP modelle (model E en X). Dit was uitgevoer deur middel van atleet-onafhanklike meganiese toetse. Tydens hierdie toetsing is die RSP van ‘n 30 cm hoogte laat val en toegelaat om vrylik op ‘n kragplatform te hop. Die resultate het getoon dat verskille tussen die piek grond reaksiekrag (In Engels, peak ground reaction force, GRF_{peak}) (model E > model X; $p < 0.05$) en maksimale RSP kompressie (ΔL) (model X > model E; $p < 0.05$). Hierdie resultate dui daarop dat die RSP model E groter styfheid as model X gehad het.

Hierdie styfheid karaktereienskappe het verband gehou met die variasie in die naelloop ekonomie van ‘n atleet wat vier maksimale anaërobiese hardlooptoetse (MART) met verskillende RSPs voltooi het. Vir die toetsing is twee styfheid kategorieë RSPs van elke model gebruik (E_{cat4}, E_{cat6}, X_{cat4}, X_{cat6}). Hierdie RSPs is lukraak aan die atleet vir elke toets toegeken. Die hardloopspoed waarteen die atleet ‘n bloedlaktaat konsentrasie van 10 mmol.l^{-1} bereik het, was die hoogste met die styfste RSP (E_{cat6}), teenoor die laagste spoed wat gevind is in die mees buigbare RSP (X_{cat4}). Dienooreenkomstig was die laagste funksionele spiervermoeïenis, soos gemeet deur ‘n afname in die voor en na toets teenbeweging sprong (In Engels, counter movement jump, CMJ), ook gevind met die gebruik van die styfste RSP (E_{cat6} 7.35% vs. X_{cat4} 24.43%).

Dit was duidelik dat tegnologie ‘n belangrike rol speel in naellope vir atlete met amputasies. Hierdie resultate toon die belangrikheid van prostese keuse. Verskille in die meganiese eienskappe van die RSPs beïnvloed beide die fisiologiese en biomeganiese response tydens die naelloop en moet gevolglik in ag geneem word wanneer ‘n RSP gekies word.

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All glory to God, my strength and comfort.

List of abbreviations

[BLa]	Blood lactate concentration
ΔL	RSP compression
A5	5° plantar flexion prosthetic setup
A6	6° plantar flexion prosthetic setup
A7	7° plantar flexion prosthetic setup
A8	8° plantar flexion prosthetic setup
A9	9° plantar flexion prosthetic setup
AL	Affected leg
ANOVA	Analysis of variance
CD	Competition density
CMJ	Counter movement jump
DJ_{AL}	Drop jump on affected leg
DJ_{UL}	Drop jump on unaffected leg
FINA	Fédération Internationale de Natation
GRF_{peak}	Peak ground reaction force
H0	Baseline height prosthetic setup
H3	3 cm height drop prosthetic setup
H6	6 cm height drop prosthetic setup
HR	Heart rate
ISMWGF	International Stoke-Mandeville Wheelchair Games Federation

ISOD	International Sports Organisation for the Disabled
IWAS	International Wheelchair and Amputee Sports Federation
MART	Maximal anaerobic running test
Re-Flex VSP	Re-Flex vertical shock pylon
RPE	Rate of Perceived Exertion
RSI	Reactive strength index
RSP	Running specific prosthesis
SACH	Solid ankle cushioned heel
SL	Step length
T12	Visually impaired track athletics classification
T13	Visually impaired track athletics class
T37	Cerebral palsy track athletics class
T42	Unilateral or bilateral transfemoral amputee track athletics class
T43	Bilateral transtibial amputee track athletics class
T44	Unilateral transtibial amputee track athletics class
t_c	Contact time
t_f	Flight time
TEM	Technical error of measurement
UL	Unaffected leg
VALR	Vertical average loading rate
VO_2	Oxygen consumption
VO_{2max}	Maximal aerobic capacity

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Chapter 1

Background

Introduction

For athletes with lower limb amputations, sprinting requires the use of a lower limb prosthetic. These prosthetics have become very advanced and more sport-specific and as of 1992, with the removal of the heel component of the prosthetic, they have been termed running specific prosthetics (RSPs). With the increasing growth and public awareness of the Paralympic Games, the athletes have become more professional and fine tuning performance has become critical. Therefore, understanding the interaction between the athlete and the prosthetic is crucial to the development of athletic performance.

Due to limitations in the literature, as well as the fast rate of progression in the RSP technology, selection of RSPs specific to an athlete’s needs and characteristics (i.e. anthropometry, running style, and strength) is challenging. This can be explained by the limited understanding of the mechanical characteristics of the RSPs and the lack of knowledge regarding the influence of these features on athletic performance. Therefore the aim of this study was to assess the biomechanical and physiological effects of the mechanical characteristics of different RSPs on an athlete’s sprinting performance.

History of the Paralympic Games

The first Paralympic Games was hosted in Rome in 1960 and was organized by the International Stoke Mandeville Games Federation (ISMWGF) (32). Today this federation is known as the International Wheelchair and Amputee Sports Federation (IWAS). The Games hosted 400 wheelchair athletes from 23 countries and athletes participated in eight sports over the course of eight days. In 1976 the Paralympic Games in Toronto had grown to 1657 participants, which also included 261 athletes with amputations and 187 athletes with visual impairments (38). After these Games, the International Sports Organization for the Disabled (ISOD), under the presidency of Professor Sir Ludwig Guttmann, president of ISMWGF, was incorporated into the Paralympic Games. Since then, the Paralympic Games has grown exponentially. The London 2012 Paralympic Games included 4237 athletes from 164 countries and they competed in 20 different sports (23, 31).

Similar to that of able-bodied sport, technological advances in sporting equipment is also evident in disability sport (7). One of the prominent developments involves the RSP used by athletes with amputations. In 1981 the Seattle foot was designed which was the first energy storage prosthesis designed for clinical use (11). This was followed by the flexible keel running prosthesis, the Flex Foot, first seen at the Paralympic Games in 1988. Four years later many athletes participated with the RSP without a heel (Figure 1) (30). Since then RSPs have gone through many technical improvements to the socket and prosthetic. In sprinters with above knee amputations (T42), notable advances were made to the prosthetic knee.

Figure 1 The running prosthesis with a heel (left) was first seen in the 1988 Paralympic Games (Seoul) and the modern running specific prosthesis (right) was introduced in 1992.

The changes found in the RSPs included the shape of the RSP, with the posterior bend becoming considerably more pronounced. The current RSPs are also mounted on the back of the prosthetic socket in comparison to originally being mounted on the anterior tibia. Furthermore, improvements in the stump socket interference have seen a progression from the socket being held in place by straps tied around the waist and leg, to silicon liners that either create a vacuum between the stump and the socket, or using a locking pin found on the liner to lock the stump into place. Progress in material science has also led to RSPs that can tolerate greater forces, yet are lighter (16). Generally in elite sports, as the popularity of the sport increases, the funding available for the sport increases. Subsequently, more athletes have the opportunity to turn professional and make a living through their sport. More funding also means that athletes can afford a more scientific approach to their sport, as well as full time coaching staff and trainers. Although limited in comparison to other sport such as swimming, track running has also been affected by technological advances, for example, changes in track surface, starting blocks and timing systems.

Factors determining sprinting performance have been explored by various researchers. Factors in four main categories have previously been described namely 1) environmental, 2) mechanical or equipment, 3) biomechanical, and 4) psycho-physiological (25). Although amputee sprinters are exposed to the same environmental factors as able-bodied sprinters, athletes with lower limb amputations have less skin surface area and this could be detrimental to thermoregulation (14). However, for the purpose of this study, the focus will be placed on the biomechanical, physiological, and prosthetic influence on performance.

Biomechanical background

Kinematics

Running speed is essentially determined by two parameters, namely step length and step frequency (40), where a dynamic link exists between step length and step frequency. In order to achieve peak performance, an athlete has to find a balance between these two variables, as increasing the one could lead to modification of the other (20, 24). Very little literature is available regarding the influence of RSPs and more specifically how different RSP mechanical properties influence sprinting parameters.

Mixed results have been reported in terms of stride frequency in running with prosthetics. Two studies compared an elite bilateral transtibial amputee with performance matched able bodied controls. One of these studies found no difference in the stride frequency (2), whereas the other found that the stride frequency was higher in the amputee compared with the controls (39). The higher stride frequency in the latter study was said to be due to a 14.1% longer contact time accompanied by a 34.3% shorter aerial time in the bilateral amputee sprinter (39). Interestingly, the study by Brüggemann *et al.* (2008) was completed with over-ground running, whereas the study of Weyand *et al*. (2009) was done on a motorized treadmill. The difference in treadmill and over-ground gait has previously been reported (33) and could possibly have influenced the kinematics of the athletes, and therefore have led to this discrepancy in the literature.

Research in unilateral amputee running has mainly focused on the difference in stride parameters between the affected and unaffected leg. It is felt that the unaffected leg of unilateral amputees can easily act as a control for comparative purposes (15). This may be true, however the influence of the asymmetry, which is generally evident in these athletes, is unknown. Grabowski *et al.* (2010) found a statistically significant difference in the step frequency of the unaffected (UL) and affected leg (AL) in elite T44 sprinters (n = 6) (UL > AL, $p < 0.05$). This testing was completed on a treadmill at increasing treadmill speeds up to maximal. It was assumed that the difference in the inertial properties of the affected and unaffected limb due to the variation in mass would create differences in swing time. However, the difference in step frequency was not due to differences in swing time, but rather due to variations in the flight time. This study did not include stride length results, and further research is needed to determine whether asymmetry is present in this regard. However, from these results it can be speculated that an asymmetry will exist. A recent retrospective video analysis of the World Championships in 2011 and the 2012 Paralympic Games indicated that athletes with unilateral transtibial amputations were more prone to asymmetry in contact time between their two legs in comparison to bilateral amputees (10). This supports the notion that there is a difference in step frequency between the AL and UL, and may indicate that difficulty in controlling the RSP may be a cause for the asymmetry in the two legs.

It is known that spring stiffness is linearly correlated with stride frequency in intact legs (12, 28). This spring stiffness, or as referred to in human running, leg stiffness, is determined by factors such as neuromuscular activity, tendons, ligaments and the passive stiffness of the joints (4, 13). When hopping on a prosthetic, it was found that the stiffness of the prosthetic influences both the contact time and the flight time of the hops (18). However, no relationship was found between leg stiffness and stride frequency or contact time in a study on the UL of unilateral transtibial amputees during running (27). Furthermore, when comparing the AL and UL of unilateral amputees, McGowan *et al.* (2012) found no statistically significant difference in the stride frequency between the AL and UL. In transfemoral amputees, the added mechanical structure on the hydraulic knee may increase the stiffness of the AL to levels greater than that of the UL (26). Further research is therefore necessary to understand the relationship between prosthetic stiffness and stride parameters.

Kinetics

It is to be expected that there will be kinetic differences in sprinting with and without a prosthetic limb. Because kinetics deals with forces and momenta, mass distribution will be expected to influence these factors. It has been suggested that mass distribution changes of the lower limb in the absence of neuromuscular control has a great effect on the impact force peak (22). This is critical in an amputee sprinter as they are not able to modulate the neuromuscular control of the prosthetic component.

An overwhelming portion of the literature has found differences in the ground reaction forces between intact limbs and prosthetic limbs. In order to propel the body forward during sprinting there are three main forces working namely, ground reaction force, gravitational force and wind resistance force. The athlete has the most control over the modulation of the ground reaction force (21). It was found that in bilateral amputee sprinters the peak vertical ground reaction force (2, 27), as well as the average vertical ground reaction force during stance (39), was lower than that of able-bodied controls during maximal and submaximal running speeds.

When testing unilateral amputees there are three combinations of comparisons that can be drawn for investigative purposes. The first comparison can be drawn between the AL and UL of the unilateral amputees. This will give an indication of the asymmetry found within the athlete. The second is between the AL of the unilateral amputees and the biological legs of able-bodied runners, and thirdly the difference between the UL of the unilateral amputee and the biological legs of the able-bodied runners. These comparisons will give an indication of the deficit caused by the amputation and whether that translates to a compensation or a deficit in the unaffected side as well (Figure 2).

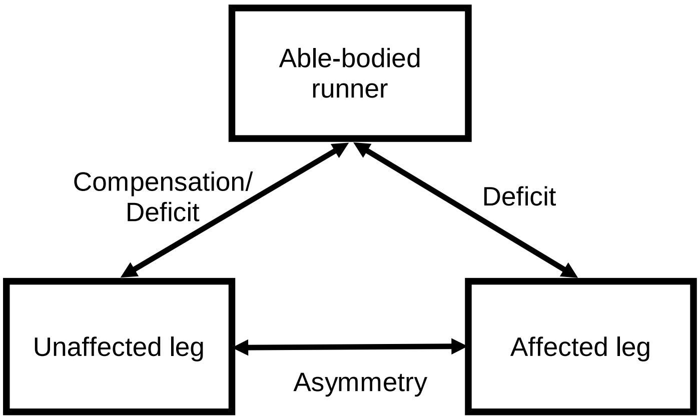

Figure 2 Graphical representation of comparisons drawn between unilateral amputees and able-bodied controls

It was also found that there is significant asymmetry in runners with unilateral transtibial amputations, as indicated by the lower ground reaction force in the AL in comparison to the UL (5, 15, 27, 36). Similarly, lower ground reaction forces were measured in the AL of unilateral amputee runners compared to able-bodied controls, however, the UL reached similar ground reaction forces to the control groups (27, 36). Therefore, it is not a case of the athlete being physically inferior to the controls, but rather that the prosthetic is limiting the amount of ground reaction forces that can be reached. Vertical ground reaction force has been found to be related to running speed (29, 40) and it can therefore be considered a predictive variable in sprinting performance. It may be this knowledge that led Grabowski *et al.* (2010) to state that the deficit in ground reaction force production in sprinting with prosthetic legs could be a major limiting factor in the maximal speed obtained by these runners. This lower ground reaction force found with the use of a RSP has been found to be accompanied by a lower vertical average loading rate (VALR) at sub-maximal speeds (17). The VALR indicates the rate at which the vertical ground reaction force increases or in other words the impact of the collision of the foot with the surface. It was felt that the decreased VALR was a protective action intended to prevent soft tissue injury due to the impact on the stump, which is not adapted to bearing loads (35).

We know that the mass of a RSP is less than that of an intact lower limb. This will influence the inertial properties of the segment in comparison to the intact limb. This is evident in the decreased mechanical work reported by Brüggemann *et al.* (2008). The lower limb muscular work in five able-body and five unilateral transtibial amputees at sub-maximal speed was calculated by determining the work done by each segment and adding the sum of the total positive work and the absolute value of the total negative work together (9). These results indicated that during the swing phase of running, the total muscle work in the UL (102.8 ± 20.3 J) of the unilateral amputees was greater than that of the AL (81.3 ± 11.9 J) as well as the able-bodied participants (78.4 ± 10.9 J). The total muscular work of the AL was similar to that of the able-bodied participants. This is thought to be a compensative strategy to transfer energy during the push-off phase of the intact limb to compensate for its decreased ability to produce force.

Physiological background

The muscle loss due to an amputation poses an interesting debate regarding the metabolic cost of ambulation. It can be thought that the loss of the limb will cause compensatory actions by other muscles and this could lead to increased metabolic strain on the body, whereas the decrease in muscle mass could also simply cause a decrease in metabolic cost. Gailey *et al.* (1997) stated that there are various factors that could influence the metabolic cost of walking in persons with lower limb amputations such as differences in the inertial properties of the prosthetic leg, uncoordinated movement in the limb and asymmetry between limbs, deviations in normal biomechanical movement, loss of potential energy in the system, loss of effective muscle mass, and thermoregulatory problems. Although these factors were suggested to affect walking, it is possible that they could also contribute to variations in the physiological response to sprinting in athletes with lower limb amputations. Unfortunately the heterogeneity in athletes with lower limb amputations, imposed by the amputation (e.g. stump length, reason for amputation, unilateral or bilateral amputation), makes it difficult to come to a conclusion on the influence of the limb loss on the physiological systems.

It has been found that both the oxygen consumption (VO_2) (14.3%) and heart rate (30.8%) were significantly greater during walking in a group of unilateral transtibial amputees than in a control group (14). However, this study was completed with walking prosthetics which are stiff in comparison to RSPs. The metabolic cost of movement in amputee runners has been thought to decrease with an increase in compliance due to the energy return of the prosthetic (1, 19, 41). Running specific prosthetics are manufactured to be more compliant than walking prosthetics and it could therefore be possible that they may not increase the metabolic cost to the extent of a walking prosthetic. This effect is evident in the differences in physiological responses found between a traditional walking prosthetic and a RSP, where the VO_2 (14%) and heart rate (9%) in six healthy runners (five unilateral and one bilateral) were significantly lower in the RSP condition (1). Furthermore, the influence of the stiffness of the prosthetics was found to be influenced by speed, in which the greater the speed, the more energy is stored in the prosthetic and therefore the greater the energy return (19, 41). It could therefore also be that a RSP increases metabolic cost of sprinting to a lesser extent than seen in walking.

Brown *et al.* (2009) studied the different physiological responses imposed by either a traditional prosthetic or a RSP in six amputees (five unilateral and one bilateral transtibial amputees). The results were also compared to that of a matched control group (n = 6). The effect of the energy return of the RSP is evident in the physiological difference between the two prosthetics. A significant difference was found in both the VO_2 (14%) and heart rate (9%) at the same submaximal speed between the traditional prosthetic and RSP. Interestingly the amputee group had higher heart rate and VO_2 measurements than the control group when they ran with the traditional prosthetic, but not when they ran with the RSP.

The metabolic cost of running of a bilateral transtibial amputee was found to be lower than that of elite distance, sub-elite distance, and 400 m able-bodied runners, respectively. Due to the small sample size it was not possible to complete traditional statistical analysis on the data, however, the authors found that the difference between the amputee and the 400 m sprint specialists was greater than two standard deviations of the 400 m specialists' performance which could indicate a dissimilarity between the two groups. Similarly, the maximal oxygen consumption of the amputee athlete was 7.6% lower than that of 400 m sprint specialists at the same maximal speed. This did not however have an influence on the fatiguing profile of the athlete, where the sprint endurance of the athlete with the amputation was similar to that of the able-bodied runners when normalized for aerobic reserve speed. The relevance of metabolic cost in sprinting, especially the 100 m, is debatable due to the utilization of primarily oxygen-independent energy systems in short sprints. During short maximal speed running, the oxygen-independent systems contributes up to 70 to 80% of the energy required (34), however, the oxygen-dependent energy system plays a greater contributing role in energy production in longer distance sprints such as the 400 m.

Adaptations made to the prosthetics

There are various prosthetic manufacturers that make RSPs. Companies usually have a range of RSPs, made to serve different purposes. Essentially these RSPs differ from each other in shape and stiffness. Different spring characteristics are aimed at favouring different track events. Most research investigates the influence of different prosthetic components on walking. This is partly due to the fact that the modern day RSP has only been used in competition since 1992, and they are also utilized by only a small portion of the population.

It was found that the energy storage prosthetics for running allowed for greater peak power outputs, with these feet also having greater spring efficiency (84% Flex Foot®, 52% Seattle foot®, 31% solid ankle cushioned heel) (8). Spring efficiency is an indication of how much energy is produced by the prosthetic relative to the amount of energy put into the prosthetic. Other related literature indicates that prosthetics with better spring efficiency induce lower metabolic cost on individuals during submaximal running (1, 19). In a study by Buckley (1999), it was found that the most effective RSP (either Cheetah® or Sprint Flex®) varied between two unilateral amputees. The amputees each preferred a different RSP, and this preference was related to that which allowed for the best power production distribution in the athlete (6). It is therefore possible that it is not only the efficiency of the spring that is important in the athletic performance, but also the synergistic relationship between the RSP and the athlete’s running style.

It is difficult to compare findings of walking with that of running due to kinetic and kinematic changes occurring with an increase in running speed (3). However, it is important to note that walking studies established that changing the prosthetic properties and alignment causes changes in the wearer’s biomechanics and physiology. Changing the plantar flexion angle of prosthetic walking feet also have a significant influence on the metabolic cost of walking at 4.0 km.h^{-1} and 4.8 km.h^{-1} (37). Similar dynamics can be expected for RSPs.

Conclusion

The technology in running with RSPs is changing at a rapid rate. In a 20 year time span a vast amount of research and development has gone into these prosthetics, which was not necessarily matched by scientific literature on RSPs and its effect on athletic performance. RSPs influence athletic performance in a variety of ways, and as of yet it is not possible to draw conclusions regarding the differences in running gait and physiology between not only amputees and able-bodied sprinters, but also between unilateral and bilateral amputees.

Problem statement

Limited literature regarding RSP characteristics and its accompanying influence on athletic performance (both biomechanical and physiological) makes prosthetic selection for athletes extremely difficult. The purpose of this investigation was to examine the mechanical properties of different RSPs and the influence thereof on athletic performance.

In the following chapters an attempt is made to better understand RSP technology and its significance on athletic performance.

Chapter 2

In a retrospective analysis of past Paralympic performances, this chapter addresses the first research question: Is there evidence that the technical development of RSPs had a significant effect on the performance improvements of athletes in the T42 - T44 men's classes from 1992 to 2012?

Chapter 3

In order to better understand the mechanical differences between RSP models, this chapter addressed the second research question: What mechanical differences exist between different RSPs in terms of stiffness and shape? In order to do so, athlete independent mechanical testing on eight RSPs were performed. The elastic characteristics and its relationship to performance characteristics were measured.

Chapter 4

Four of the eight RSPs tested in Chapter 3 were tested on an athlete completing maximal anaerobic running tests to determine their influence on sprinting economy and stride parameters. This relates to the final research question: What effect does different RSP characteristics (stiffness and shape) have on the physiological responses of the athlete during a maximal anaerobic running test?

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Chapter 2

Paralympic sprint performance between 1992 and 2012

The following article has been accepted for publication in the International Journal of Sports Physiology and Performance – February 2015

Grobler, L., Ferreira, S. & Terblanche, E., 2015. Paralympic sprint performance between 1992 and 2012. *International Journal of Sports Physiology and Performance*. (10):1052-1054

Abstract

The Paralympic Games have undergone many changes since its inception in 1960, one being the advances made in running specific prosthesis (RSP) for track athletes with lower limb amputations. *Purpose.* The purpose of this study was to investigate the sprinting performance changes in athletes with lower limb amputations since 1992 to assess whether the influence of developments in RSP technology is evident. *Methods*. The results of the Olympic and Paralympic Games ranging between 1992 and 2012 for the 100m and 200m were collected and performance trends, percentage change in performance and competition density (CD) were calculated. *Results.* The results indicate that the greatest performance increases were seen in athletes with lower limb amputations (T42 = 26%, T44 = 14%). These performance improvements were greater than for Olympic athletes (<3%), as well as Paralympic athletes from other selected classes (<10%). The T42 and T44 classes also showed the lowest CD values. *Discussion*. These results suggest that although there is an overall trend for improved Paralympic sprint performances, RSP technology has played a noteworthy role in the progression of performances of athletes with amputations. It is also hypothesized that the difference in the performance improvements between the T42 and T44 classes is due to the level of disability and therefore the extent to which technology is required to enable locomotion. *Conclusion*. It is evident that RSP technology has played a significant role in the progression of performances in athletes with lower limb amputations.

Keywords: Amputees, Sprinting, Performance trends, Technology, Running specific prosthesis

Introduction

The first Paralympic Games was hosted in Rome 1960 with 400 competitors. Since then the number of participants has increased more than fourfold and also includes a wide range of disabilities. Similar to able-bodied sport, technological advances in sporting equipment is evident in disability sport. One of the prominent developments involves the running specific prosthesis (RSP) used by athlete with amputations. The flexible keel running prosthesis was first seen in the 1988 Paralympic Games. Four years later many athletes had the heel of the RSP removed and since then many technical improvements in design and composition followed.

The aim of the ongoing changes in RSPs is understandably to improve the athletes' performance. Various shapes of RSPs are on the market today, with a visually more pronounced bend at the rear than the 1988 RSPs. Previously the blades used to attach to the front or middle of the socket, whereas it is now more commonly attached to the rear of the socket, due to the benefit it seems to have on running performance. The stump-socket interphase also improved from straps tied around the athlete's waist to a silicon liner that creates a vacuum to the attach socket to the stump.

Studying athletic performance trends over time affords us the opportunity to gain insight into external factors affecting performance. Previous research have highlighted factors such as economical advances[1], media coverage[1] and popularity[1,2], coaching and training[1,2,3,4], technology and equipment[1,3,4], environmental conditions[3], as well as professionalism of the ahtletes[4].

The most prominent example of how technology can affect sport performance occurred in 2009. Researchers found that the introduction of technical swimsuits (Speedo LZR Racer) was the main reason for the extraordinary improvements in swimming performance[2]. At the Fédération Internationale De Natation (FINA) World Championships (Rome 2009), 43 new world records were set. In 20 long course events, men broke 15 records and women 17, of which all men's records and 11 women's records still stand today. It is reasonable to think that RSPs had similar ergogenic effects on Paralympic sprinters than technical swimsuits on Olympic swimmers, albeit not necessarily to the same extent.

Thus, the aim of the investigation was to track the sprinting performances of athletes with either above knee or below knee amputations from 1992 to 2012 and to assess whether advances in RSP technology is evident in the progression of sprint performances.

Methods

Results for the 100 and 200m sprints for athletes in the T12, T13, T37, T42 and T44 classes during the past six Olympic and Paralympic Games were gathered from two websites[5,6]. The classes represent those with visual impairments (T12 and T13), cerebral palsy (T37) and above (T42) and below (T44) knee amputations including both single and double amputees.

Athletes' performances in the Olympic Games were included as a reference to indicate the effect of professionalism and training science. The T12, T13 and T37 athletes are far less dependent on technology compared to athletes with lower-limb amputations. Therefore, assuming all Paralympic athletes made similar advances in performance due to more dedicated and scientific training, greater changes in the T42 and T44 classes may point to the contribution of RSP technology.

Performance trends

The performances of athletes in the 100m and 200m for each of the classes in all Olympic and Paralympic Games between 1992 and 2012 were plotted. The means and standard deviations were calculated from the race times, excluding athletes who sustained injuries during the race. Data for the T42 athletes in the 200m during the 1998 Paralympic Games are absent as the event did not take place that year.

Competition density (CD)

The competitiveness of an event is described by the competition density (CD). This was calculated using the following equation:

$$CD = \frac{n_{finish}}{(t_{last} - t_{first})} = competitors.s^{-1},$$

where n_{finish} is the number of competitors who completed the race, t_{last} is the race time for the last competitor and t_{first} is the race time for the winner. (This calculation is based on the equation for volumetric mass density in which density is given as mass per unit volume).

Results

Performance trends

The performance of the 100 and 200m finals are represented in Figure 1. Performances improved in both events from 1992 to 2012, however, in both cases the Paralympic performance improvements were greater than the Olympic improvements.

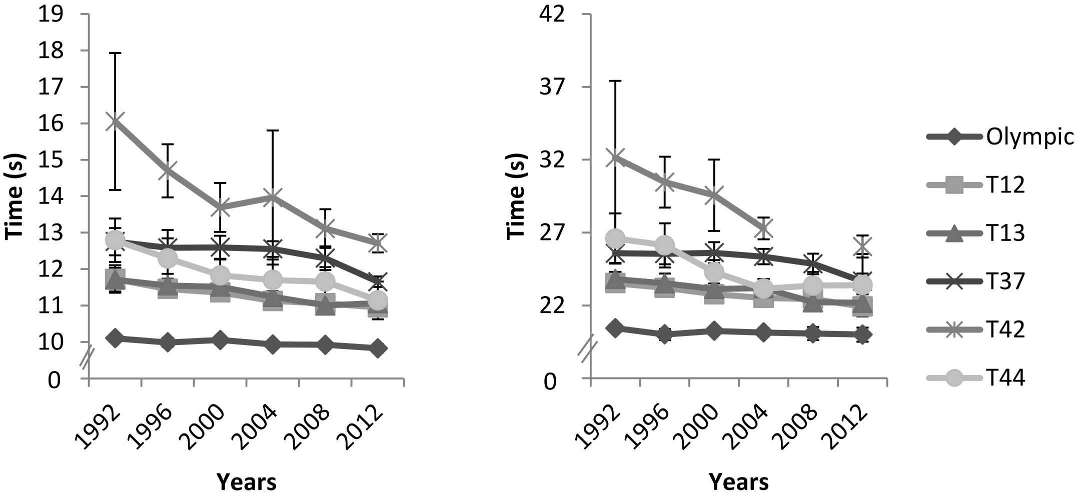

Figure 1 Mean race times (seconds) for all athletes in the different classes that completed the 100m (a) and 200m (b) race from 1992 to 2012. Data are expressed as mean ± SD.

The percentage improvement between 1992 and 2012 are depicted in Table 1. For both Olympic sprint distances there were less than 3% improvements in race times. Changes in sprint performances were similar for the T12, T13 and T37 classes (<10%), while most improvements were observed for athletes who ran with RSPs (14-26%). Nevertheless, all improvements were found to have large practical significance (Cohen's effect size > 1.15).

Table 1 Percentage change (%) in 100m and 200m performance between 1992 and 2012 for the different classes.

Class	100m Percentage change	Effect size	Confidence limits		200m Percentage change	Effect size	Confidence limits	
Olympic	2.8	2.5	1.1	3.7	2.2	1.1	0.1	2.1
T12	7.1	2.5	0.6	3.9	6.8	5.0	2.0	6.8
T13	5.8	2.2	0.8	3.2	7.4	4.4	2.4	5.9
T37	9.4	3.9	1.9	5.3	8.1	3.2	1.5	4.5
T42	26.3	2.3	1.1	3.4	23.5	1.9	0.6	3.0
T44	14.8	2.9	1.4	4.1	13.7	1.6	0.4	2.7

Competition density

The Olympic sprint results showed highest density (23.90 and 9.29 competitors.s^{-1}, respectively), whereas the T42 class was the least dense in both events (100m = 4.53 competitors.s^{-1}; 200m = 1.93 competitors.s^{-1}) (Figure 2). According to these results the variability between competitors was greater in sprinters who run with RSPs than in sprinters with other classifications.

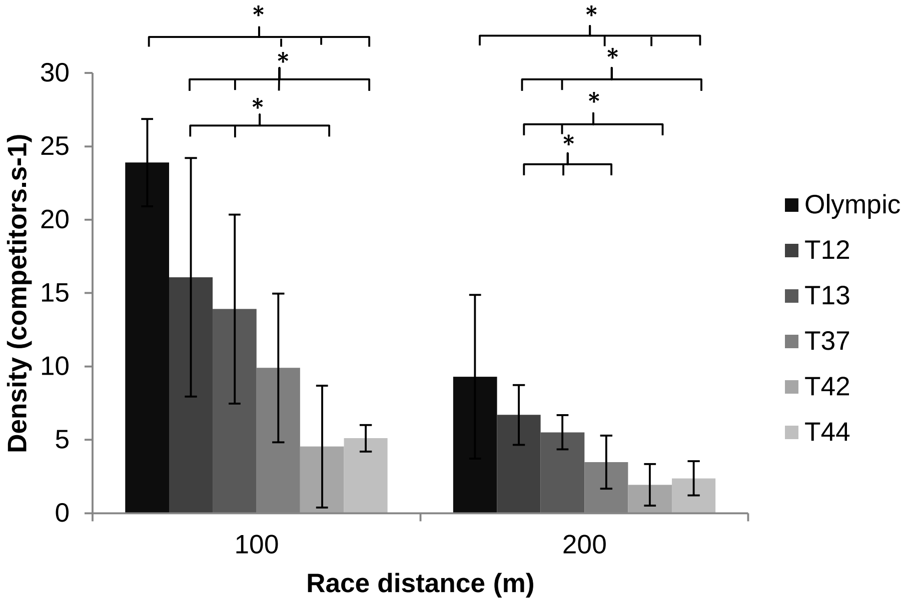

Figure 2 Competition density (competitors.s^{-1}) in the sprint events for the different classes between 1992 and 2012. Data are expressed as mean ± SD. * Statistically significant difference ($p < 0.05$).

Discussion

In general sprint performances improved since 1992 for both Olympic and Paralympic athletes. However, the results showed that athletes who run with RSPs experienced greater performance increases (T42 = 15%; T44 = 16%) than Olympic sprinters (1.5%), as well as sprint athletes with other disabilities (T12 = 6%; T13 = 8%; T37 = 9%). The large difference in performance improvements for athletes in the T42 and T44 classes compared with the Olympic sprint results suggest that there is another factor, other than training development, that effected the changes. The difference in performance changes in the T42 and T44 classes and the other Paralympic classes represented here also point towards the fact that performance improvements in athletes with amputations are likely attributable to factors other than the growth of the sport and the application of training science. Thus it is reasonable to argue that advances in RSP technology had a significant effect on the performance improvements of athletes with amputations, as these are the only classes using these RSPs for locomotion. Since 1992 the shape and composition of the prostheses have been improved in an attempt to enhance the biomechanics (i.e. running style) and physiology (i.e. economy of running) of the athlete. Changes to the RSPs could also have influenced the training of these athletes, enabling them to train more or train more effectively; however this has not been documented. Furthermore, differences between T42 and T44 performances may be a reflection of a more pronounced ergogenic effect of RSP technology on athletes with above knee amputations.

The findings in this study also indicated that the T42 and T44 classes had the lowest CD values (varied sprint times), while the Olympic sprint races showed large CD values (closer competition). This is not an unexpected finding and can be explained by at least three factors. Firstly, high level sport participation for the physically disabled is still growing and therefore factors such as access to coaching, training time, professionalism and popularity will play a key role in this difference. Secondly, one can also expect that differences among participants in a specific class, such as stump length, when the amputation was acquired, reason for amputation, and the lifestyle maintained before the amputation, will also contribute to the lower competition density in sprinters with lower-limb amputations. Thirdly, athletes in the T42 and T44 classes are very dependent on RSPs to be competitive. However, not all countries would have enough resources to provide their athletes with the latest technology. Variations in RSP technology among athletes may also explain the larger variation in sprint performance.

Research exploring the benefits of RSPs found that using RSPs have no physiological benefits compared with intact limbs. However, there were biomechanical differences[7] such as lower vertical ground reaction forces at maximal speed running. It therefore seems that the strain on the body is similar in these athletes compared to able-bodied athletes, however the performances are poorer due to the biomechanical differences. Technology may have the ability to overcome these biomechanical differences, but regulation strategies will have to be set in place to maintain fair competition.

Practical application

For athletes to remain competitive, they will not only need access to the latest RSP technology, but they will also need the scientific backup to match him/her with the most appropriate RSPs for the specific event. It was not possible to determine which specific aspects of RSP technology was the main contributing factor to the performance trends, as limited information is available on blade-specific characteristics.

Conclusion

The findings in this study appear to indicate that advances in RSP technology played a significant role in the progression of sprint performances of athletes with amputations between 1992 and 2012. A further indication of the important role of RSP technology in the performances of these athletes is that athletes who are more dependent on RSPs for locomotion (T42) showed the largest improvements in performance, as well as greater variation in performance time among athletes in a race.

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Chapter 3

Characterisation of two running specific prosthetic models

The following article has been submitted for review to the Journal of Prosthetics and Orthotics International – August 2015

Grobler, L., Ferreira, S., Vanwanseele, B., & Terblanche, E., 2015. Characterisation of two running specific prosthetic models.

Abstract

The need for information on the properties of running specific prosthetics (RSP) has previously been voiced. Such information is necessary to assist in prosthetic selection for athletes with lower limb amputations. This study aimed to determine differences in the characteristics of two commercially available RSPs. The RSPs were tested (in an experimental set-up) without the external interference of athlete variations in performance. Four stiffness categories of each RSP model (E and X) were tested at seven alignment setups. Results for peak ground reaction force (GRF_{peak}), contact time (t_c), flight time (t_f), reactive strength index (RSI) and maximal compression (ΔL) were determined during controlled dropping of RSPs onto a force platform with different masses attached to the experimental setup. No statistically significant differences were found between the different setups of the RSPs, however, differences between the categories were found for the 38 kg drops. Statistically significant differences were found between the two models for all outcome variables (GRF_{peak}, E > X; t_c, X > E; t_f, X > E; RSI, E > X; ΔL, X > E; $p < 0.05$). These findings suggest that the model X RSP stores more elastic energy leading to a greater performance response in comparison to the model E RSP.

Clinical relevance

Insight into the RSP properties and an understanding of its characteristics has implications for athlete's prosthetic choice. Physiologically and metabolically a short sprint event (i.e. 100 m) places different demands on the athlete than a long sprint event (i.e. 400 m) and the RSP should match these performance demands.

Background

Since 1992 the running specific prosthesis (RSP) has been the prosthetic of choice in sprint athletes with lower limb amputations, however, very little literature is available on the characteristics of the RSPs. The nature of this carbon fibre prosthetic foot is one of energy storage and return. Thus it mimics the function of the lost limb it replaces, although there is still debate on how much function, and in what manner it replaces function[1].

In order to optimise an athlete's performance and comfort levels, it is essential to understand the physical and mechanical differences among RSPs. These characteristics have been investigated in walking prostheses[2], but not in RSPs. The prescription and selection of RSPs by athletes are thus primarily based on the athlete's subjective perception of comfort and very little on scientific facts.

Various prosthetic legs are available for athletes with amputations. These RSPs essentially differ in terms of shape and stiffness. Dyer *et al.* (2014) found that variations in the stiffness of the prosthetic can be achieved by changing the composition of the carbon fibre prosthetic without changing the shape of the prosthetic. This allows for athletes in different weight classes using the same prosthetic shape but different stiffness', in other words a heavier athlete will use a stiffer RSP. In sprinting, these differences could impact the performance indicators such as the ground reaction force and stride frequency of an athlete. Ground reaction force is considered one of the major performance predictors in sprinting[3]. Stiffness and ground reaction force are also known to be related and thus by changing the stiffness of an athlete's RSP the performance of the athlete could potentially be affected[4].

To date most of the research on RSPs has been physiological in nature and focused on the athlete, with very little information available on the characteristics of the RSPs in isolation. Dyer *et al.* (2013) proposed that static loading could be used to test the stiffness characteristics of RSPs. They found the test to be highly repeatable with the coefficient of variation ranging between 0.1% and 1.7%, however, with regards to the dynamic characteristics and specifically characteristics pertaining to sprint performance[5], no literature is available on the differences that may exist between two prosthetics manufactured for different sprint distances. The 100 m and 400 m sprints are physiologically and metabolically very different from one another. It is expected that the prosthetics would be manufactured to address the key performance indicators of these two race distances.

Athletes with amputations will be better served if scientists have a better understanding of the mechanical characteristics of RSPs. The aim of this study was therefore to assess how variations in stiffness and contact alignment of two types of RSPs influence the ground reaction forces during drop testing.

Methods

Two different models (E and X) of commercially available RSPs from the same company were tested. Four different stiffness categories of each of the models were used (Table 1). The ground reaction forces were measured when dropping these RSPs onto a force platform, while two dimensional video analyses, recording at 120 frames per second, was utilized to determine the compression of the RSP. The RSPs were attached to a prosthetic socket made specifically for this testing setup (Figure 1). The socket-RSP attachment allowed for variations in the plantar flexion angle, as well as the attachment height of the RSP on the socket. The RSP-socket complex was then attached to a rig and kept in an upright position while dropped onto a force platform. The RSPs were dropped with three different masses attached to it, namely 28, 38 and 48 kg. Selection of the 28 kg mass was based on the fact that the prosthetic socket weighed 8 kg and the Olympic bar used with the rig weighed 20 kg. For each of these masses, seven alignment setups were used per RSP (baseline with two height and five angle variations). Each drop was repeated three times, adding up to a total of 63 drops per blade.

Table 1 Stiffness categories used in this study and the patient weight scale for which each RSP is prescribed

Stiffness category	**Cat 3**	**Cat 4**	**Cat 5**	**Cat 6**
Weight (kg)	60 – 68	69 - 77	78 - 88	89 - 100

RSP setup variations

Category. For each of the RSP models (E and X), four stiffness categories were tested. These categories are determined by the manufacturer (Table 1). For the purpose of the current study, categories 3, 4, 5 and 6 were used ($E_{cat\ 3\text{-}6}$, $X_{cat\ 3\text{-}6}$), with 3 being least stiff and 6 being most stiff.

Height. The length of the RSP was adapted by sliding the RSP up and down the attachment on the socket. The maximum height of the shorter of the two RSPs (model E) was used as the baseline (H0) height setup. The distance from the tip of the toe to the bottom of the socket in this baseline setup was replicated in the model X RSP (7 cm longer than model E), so that the baseline heights were similar for the two models. From here the RSP height was adjusted to three and six centimetres below baseline (H3 and H6, respectively). All height testing was done at a 7° plantar flexion angle.

Plantarflexion angle. According to the manufacturer's guidelines, the RSP should preferably be set at a 7° flexion angle in the sagittal plane as a starting point, with adjustments being made from this position to suit the athlete. Thus, a 7° flexion angle (A7) was used as the baseline setup and the angle was increased and decreased by one and two degrees for variation (A5, A6, A8, A9). All of these tests were completed at the baseline (H0) height.

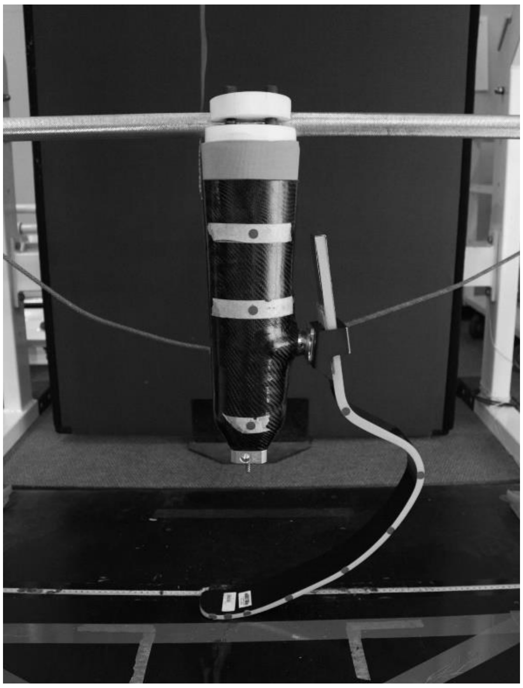

Figure 1 Custom-built prosthetic socket and RSP blade attached to a Smith Machine®

Measurements

Force was measured with a force platform at a frequency of 2000 Hz (Route Industrial Automation, RSA). The peak ground reaction force was calculated for the first drop of each trial (GRF_{peak}). The contact time (t_c) of the first drop, as well as the flight time (t_f) after the initial hop were determined with a threshold force of 40 N. Finally, the reactive strength index (RSI) was determined by dividing t_f by t_c.

Two dimensional video analyses in Kinovea 0.8.15 were completed to determine the maximal compression (ΔL) of the RSP during the drops. Video footage was captured with a Casio EX-FH 100 (Japan) high speed camera at 120 frames per second.

The Intraclass correlation for agreement was calculated for the outcome variables in each setup (GRF_{peak} = 1.00; t_c = 0.99; t_f = 0.84; RSI = 0.90; ΔL = 0.95). Absolute and relative technical error of measurement (TEM) was calculated for the outcome variables ($TEM_{absolute}$: GRF_{peak} = 21.12 N; t_c = 0.002 s; t_f = 0.005 s; RSI = 0.03; ΔL = 0.37 cm; $TEM_{relative}$: GRF_{peak} = 0.90%; t_c = 0.89%; t_f = 1.37%; RSI = 1.83%; ΔL = 3.66%).

Statistics

The mean values of the three trials for each setup were used in further analysis. Analysis of variance (ANOVA) for repeated measures was used to test for differences between the two RSP models, the different categories of RSP and the alignment setups. The Fischer's least significant difference test was used as post-hoc analysis. Statistical analysis was done using Statistica 12 (StatsSoft, USA). The significance level was set at $p = 0.05$.

Results

Trends between models and categories within the outcome variables were similar for all dropped masses, thus for simplicity only the 38 kg results will be discussed in detail.

Influence of different categories

Statistically significant differences were found between the different categories in both models for t_c ($E_{cat3} > E_{cat4\text{-}6}$; $E_{cat4} > E_{cat6}$; $X_{cat3} > X_{cat4} > X_{cat5} > X_{cat6}$) ($p < 0.05$). Statistically significant differences were found among the categories in both models for all outcome variables at 38 kg. It was found that GRF_{peak} increased, t_c decreased, t_f decreased, and ΔL decreased with an increase in the stiffness category, whereas the RSI decreased in the model E and increased in the model X RSP with an increase in stiffness category. There were no interaction effects between the model and category RSP, and the mass dropped, for GRF_{peak} (Figure 2), t_f (Figure 4), RSI (Table 2), and ΔL (Table 2) ($p > 0.05$).

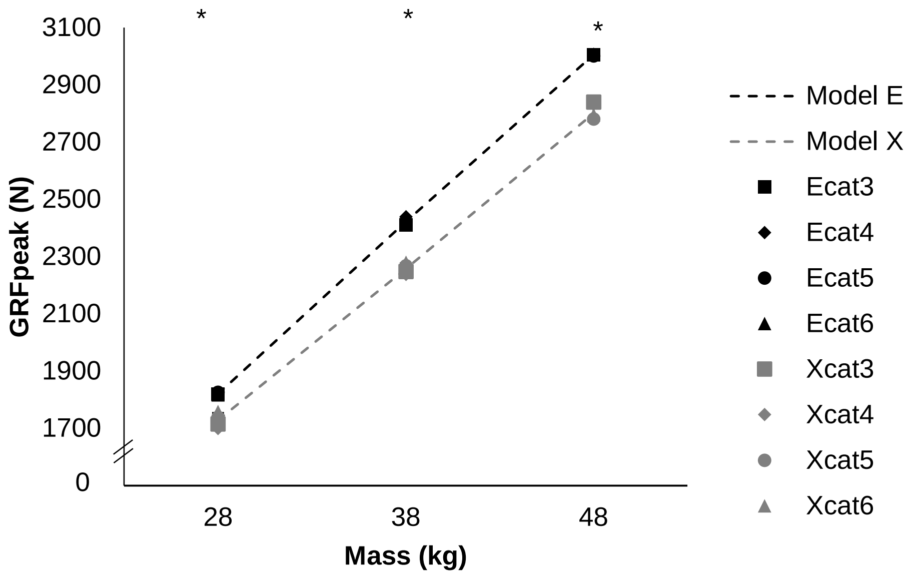

Figure 2 Mean ± SD ground reaction force peak (GRF_{peak}) (N) of the RSP models (E and X), as well as the categories of each model, using three different masses (kg). * Statistically significant difference between model E and X ($p < 0.05$).

Influence of RSP setup

The analysis of the interaction between the model and setup of the RSP, and the mass dropped with the RSP revealed no statistically significant differences between the different setups for any of the outcome variables in either model ($p > 0.05$).

Model differences

There was a statistically significant interaction effect for GRF_{peak} between the two RSP models and the different drop weights, (E > X) (Figure 2). Similarly, a significant difference was found between model E and X with regards to the ΔL (Table 2) and t_c (Figure 3) ($p < 0.05$). No statistically significant differences were observed for t_f (Figure 4) and RSI (Table 2) between model E and X ($p > 0.05$).

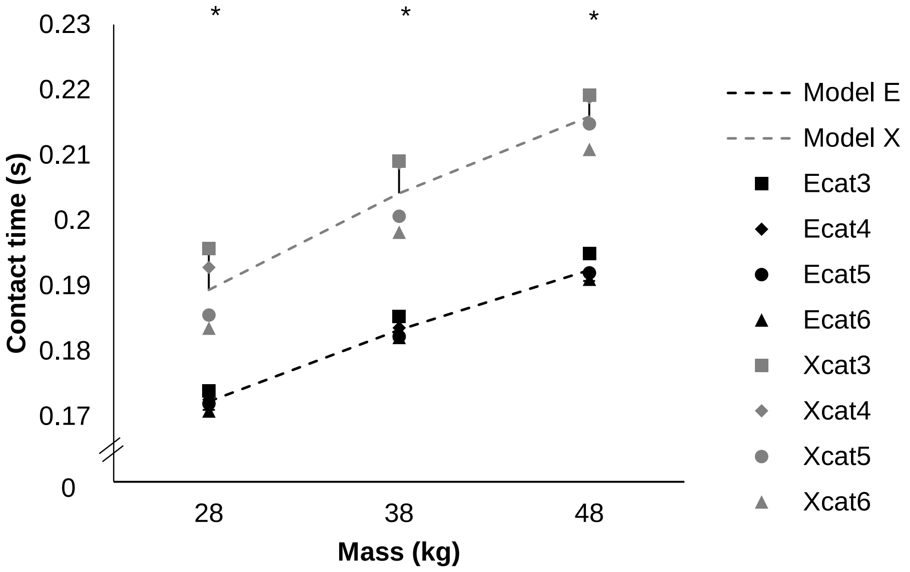

Figure 3 Mean ± SD ground contact time (s) measured in the two RSP models (E and X), as well as the categories of each model, using three different masses (kg). * Statistically significant difference between E and X ($p < 0.05$).

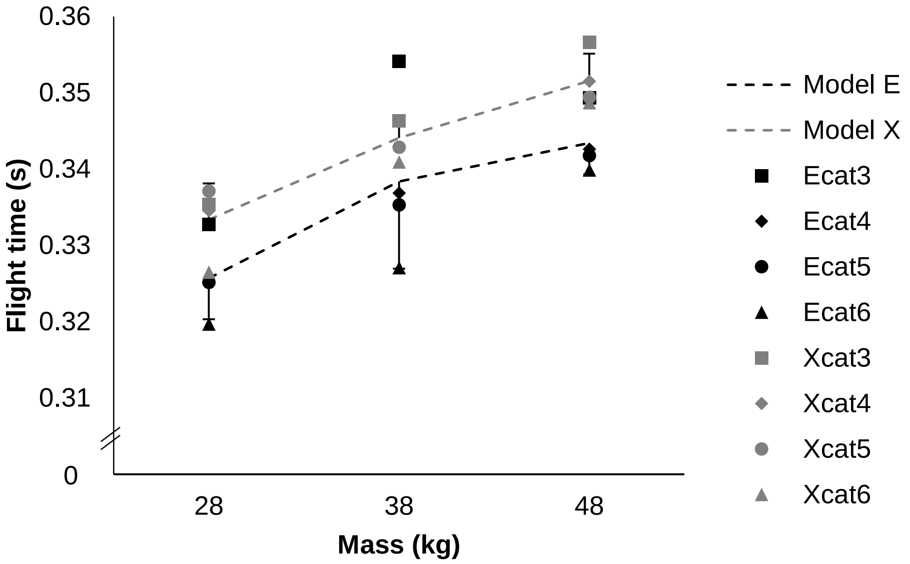

Figure 4 Mean ± SD flight time (s) measured in the two RSP models (E and X), as well as the categories for each model, using three different masses (kg). * Statistically significant difference between E and X ($p < 0.05$).

Table 2 Reactive strength index (RSI) and maximal compression (ΔL) measured in the two RSP models (E and X) whilst dropped with three different weights (kg).

	RSI			**ΔL (cm)**		
Mass	28 kg	38 kg	48 kg	28 kg	38 kg	48 kg
Model E	1.89 ± 0.02	1.85 ± 0.05	1.78 ± 0.01	7.94 ± 0.49	8.90 ± 0.56	9.83 ± 0.68
$\mathbf{E_{cat3}}$	1.91 ± 0.05	1.91 ± 0.04	1.79 ± 0.04	8.14 ± 0.49	9.91 ± 0.67	10.06 ± 0.78
$\mathbf{E_{cat4}}$	1.88 ± 0.06	1.84 ± 0.03	1.79 ± 0.03	8.22 ± 0.41	9.08 ± 0.43	10.11 ± 0.65
$\mathbf{E_{cat5}}$	1.89 ± 0.03	1.89 ± 0.03	1.78 ± 0.03	7.68 ± 0.43	8.48 ± 0.57	9.33 ± 0.58
$\mathbf{E_{cat6}}$	1.87 ± 0.03	1.80 ± 0.03	1.78 ± 0.01	7.71 ± 0.46	8.83 ± 0.34	9.84 ± 0.49
Model X	1.76 ± 0.05	1.69 ± 0.03	1.63 ± 0.02	9.90 ± 1.21	11.27 ± 1.22	12.24 ± 1.14
$\mathbf{X_{cat3}}$	1.71 ± 0.07	1.66 ± 0.06	1.63 ± 0.08	11.29 ± 0.49	12.55 ± 1.15	13.49 ± 0.89
$\mathbf{X_{cat4}}$	1.74 ± 0.03	1.66 ± 0.04	1.61 ± 0.04	10.47 ± 0.41	11.79 ± 0.52	12.45 ± 0.79
$\mathbf{X_{cat5}}$	1.82 ± 0.02	1.71 ± 0.01	1.63 ± 0.02	9.60 ± 0.37	10.94 ± 0.44	12.07 ± 0.51
$\mathbf{X_{cat6}}$	1.78 ± 0.03	1.72 ± 0.04	1.65 ± 0.03	8.26 ± 0.36	9.82 ± 0.43	10.94 ± 0.55

Discussion

This study set out to determine the differences between two models of RSP commonly used in sprint running. This was motivated by the scarcity of objective information with regards to the properties of the RSPs without the variance caused by each individual athlete. It has previously been suggested that there is a need for mechanical testing of prosthetics as a means to objectively analyse the differences between prosthetic feet[6], and though this was directed at walking prosthetics, the same is true for running prosthetics. The results of this study indicated that there is a significant difference in the maximal ground reaction force (GRF_{peak}), contact time (t_c), and compression (ΔL) between the two tested models. To the authors' knowledge, no study has previously been published where these characteristics of RSPs were measured and compared.

In order to simulate different body masses of athletes, three different masses were attached to the experimental setup. No statistically significant interaction effect was found between the model of RSP, the mass dropped and the setup of the RSP. This finding suggests that the attachment angle and height does not affect the way in which the prosthetics react to the applied load. Therefore, the RSP setup is only dependent on the athlete's personal preference and comfort, since the properties of the RSP are not influenced by setup changes. However, this does not mean that different setups may not affect the performance of the athlete, as varying results have been found on the kinematics and kinetics during walking[7] with changes in the centre of mass. Furthermore, the athlete's ability to adapt to changes in RSP setup may influence their performance outcomes. However, the results of this study do not allow for predictions on the possible influence that different setups will have on an athlete's running performance.

Significant differences in the different categories were found for the variables with the 38 kg drops. The RSP stiffness categories are specified by the manufacturers as a means of accounting for variations in athletes' body mass. Therefore, the greater the body mass of the athlete, the greater the stiffness of the RSP in order to prevent excessive compression leading to prolonged contact times while running. This is evident in the data, as both the t_c and ΔL decreased with an increase in stiffness category. The compression of the RSP acts similarly to a spring and decreases the impact by allowing for compression of the RSP. Thus, less compression leads to shorter contact time.

The GRF_{peak} results showed that the stiffer the RSP, the less energy is stored as elastic potential energy in the RSP, and more energy is transferred as force into the ground. In this case, the stiffer the RSP, the greater the GRF_{peak}. However, the storage of elastic potential energy in the softer RSPs did not result in greater jump heights (t_f) in the softer prosthetic compared to the stiffer prosthetic. This indicates that the elastic energy stored compensates for the decreased GRF_{peak}. In literature comparing amputee sprinters with able-bodied sprinters, the major limiting factor in amputee performance is stated to be the inability to produce high GRF[8], however, these results may question whether the elastic component of the RSP will not compensate for the decreased GRF.

The model E RSP also had a significantly shorter ground contact time in comparison to the model X RSP. Shorter contact time has been found to have a moderate correlation to higher running speed[9], however, in biological limbs, there is a minimum contact time reached in order to optimize the force production by the muscles during ground contact[10]. Thus it was expected that the model X RSP would display the shorter ground contact time, as the elastic response of an athlete is an important factor in the maximal speed phase of the sprint[11] and it was therefore expected that the shorter distance RSP would mimic this. The prolonged contact time in the model X RSP might be brought about by the greater compression (ΔL) found in the model X RSP, thus the RSP compresses to a greater extent and therefore lengthens the contact time.

The experimental setup in the current study is similar to that of drop jumps in athletes. Therefore, the flight time is seen as a performance variable by indirectly indicating the jump height. Given the difference in the GRF_{peak} between the models, it was expected that the model E RSP would display longer flight times than the model X RSP. However, there was no statistically significant difference in flight time between the models. It was concluded that the greater compression in the model X RSP stores more elastic energy during the braking phase of the impact, causing the force to be absorbed as elastic potential energy in the carbon fibre spring. This was evident from the lower GRF_{peak} observed in the results. During the propulsion phase of ground contact, this elastic energy is then released, leading to the extended flight time as measured in this RSP. In previous research, it was found that the spring efficiency of energy storage and return in walking prosthetic feet (Seattle foot 52%, Flex foot 84%) was greater than that of rigid walking prosthetic feet (SACH 31%)[12]. Thus, similarly to these walking prosthetic feet, there may be a difference in the spring efficiency of these two RSP models. It was observed that the stiffness of the prosthetics is dependent on the posterior curvature of the RSP, where the greater the curvature, the less stiff the RSP[13]. In the current study, the model X RSP had a more pronounced posterior curvature which could be the cause of these differences in the characteristics of the prosthetics.

The prosthetics used in this study were chosen for its specificity to sprint running. The model X prosthetic is specifically designed for short sprints, such as the 100 and 200 m, whereas the model E prosthetic is designed for longer sprints (≥ 400 m). Running speed is greatly influenced by the ground reaction forces produced by the athlete[9]. In research on athletes with lower limb amputations, it has been established that these athletes produce lower ground reaction forces in comparison to able bodied athletes[14,15], as well as lower ground reaction forces in their sound limb in the case of unilateral amputees[8,15–17]. The results of this study suggest that the model of prosthetic (E or X) has a significant effect on the vertical ground reaction force when bouncing the prosthetic. In this case the use of the longer distance prosthetic E, resulted in greater vertical ground reaction forces in comparison to the shorter distance prosthetic X. This finding is in contrast to what would intuitively be expected, namely that the prosthetics for a short sprint would produce greater vertical ground reaction forces than prosthetics for a long sprint. However, it has previously been found that the ground reaction force is lower in more compliant walking prosthetic feet in comparison to the traditional rigid prosthetic feet[18]. Although this testing was completed with walking prosthetics, it can be assumed that the same principle of material properties apply to RSPs. Therefore, similar to walking prosthetics it can be expected that the stiffness of the prosthetic will influence the force transfer of the prosthetic when dropped.

The question then is why an athlete would decide to use these prosthetics for the distances that they are specifically designed for. Perhaps the answer relates to the different phases of each race. The 100 m sprint can be divided into three main phases, namely the acceleration phase (0 to ~ 60 m), the speed maintenance/ maximal velocity phase (60 to 80 m) and the deceleration phase (80 to 100 m)[19]. Thus, the largest proportion (60%) of the 100 m sprint is spent in the acceleration phase[19]. Although a 400 m race has the same three main phases, the acceleration phase lasts about 25% of the race (0 to ~100 m)[20]. A significantly larger proportion of a 400 m sprint is spent in the speed maintenance phase (50%)[20], compared to the 20% in the 100 m

(20%)[19]. This may therefore explain why the model E prosthetic is prescribed for longer distance sprints and the model X prosthetics for shorter distances. The positive relationship between contact time and economy[21] would indicate that the model E RSP could be better suited for the 400 m sprint, whereas the need for prolonged impulse generation for acceleration and therefore extended contact times could potentially indicate the suitability of the model X RSP for the 100 m sprint.

Conclusion

It was concluded from the results that there were differences between the two tested RSP models, however, variations in the setup of the RSP had minimal influence on performance of the prosthetic. Therefore, from a practical point of view, setting up the RSP to the athletes' comfort will not influence the performance of the prosthetic. The results further indicate that these two models of prosthetic significantly differ from each other, and that more research is needed to further the knowledge of the different RSPs available in order to assist athletes and coaches in determining the optimal RSP for the athletes' demands.

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Chapter 4

The influence of different running specific prosthetics on sprinting economy

The following article will be submitted to the Journal of Sport Sciences

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Abstract

The new-found professional environment within which athletes with lower limb amputations compete calls for more knowledge and understanding regarding the relationship between prosthetic characteristics and athletic performance. This study investigated the influence of different running specific prosthetics (RSPs) on the sprinting economy of a unilateral transtibial amputee sprinter. The athlete completed four maximal anaerobic running tests (MART) with four different RSPs. Pre and post-test, the athlete also completed three counter movement jumps (CMJ) and three single leg drop jumps on both the affected (DJ_{AL}) and unaffected leg (DJ_{UL}). Both physiological and biomechanical variables were influenced by the stiffness of the RSPs at a submaximal running speed of 21 $km \cdot h^{-1}$. A relationship was found between RSP stiffness and the fatigue measured during the CMJ post-test. From the results it seems that the RSP stiffness influences the work done by the athlete, thereby influencing sprinting economy. This in turn affects the fatigue induced by the exercise. Therefore, increasing RSP stiffness improves sprinting economy.

Introduction

Performances in sprint athletes with lower limb amputations have significantly improved over the past few years. Athletes now compete in a very professional environment similar to able bodied athletes. Thus continuous improvements in an athlete's performance is of great importance. An important component of performance enhancement lies in the running specific prosthetic (RSP) that they use during sprint running. This may involve both design improvements of the prosthetics, as well as improvement in the athlete-prosthetic interaction.

A RSP is essentially a carbon fibre leaf spring attached to the distal end of an amputated lower limb. It enables elite athletes to achieve 100 m sprint times within 1 s of the able bodied world record. As the Paralympic movement grows and the sport becomes more competitive, athletes are constantly striving for improvements in performance that will set them apart from the rest of the field. For athletes with lower limb amputations, optimising the RSP could hold valuable advantages.

One of the major problems facing athletes in need of a RSP is the lack of information regarding the differences between RSPs. Research to date has mostly focused on whether the RSP gives an athlete an unfair advantage (Brüggemann, Arampatzis, Emrich, & Potthast, 2008; Hassani, Ghodsi, Shadi, Noroozi, & Dyer, 2014; Weyand et al., 2009) and what differences there are between a leg with a RSP and a biological limb (Arellano, McDermott, Kram, & Grabowski, 2015; Grabowski et al., 2010; Hobara, Kobayashi, & Mochimaru, 2015; McGowan, Grabowski, McDermott, Herr, & Kram, 2012; Trabelsi, Achard De Leluardière, & Lacouture, 2005). Most of the research indicate that athletes with RSPs achieve their performances in a biomechanically very different manner compared to able bodied runners. It has consistently been found that the ground reaction forces are significantly lower with the use of a RSP in comparison to biological limbs (Brüggemann et al., 2008; Grabowski et al., 2010; McGowan et al., 2012; Weyand et al., 2009). Data on kinematics have been mixed. In general it seems that athletes running with RSPs are able to reach similar metabolic effects during incremental exercise tests (VO_{2max} and heart rate) (Brown, Millard-Stafford, & Allison, 2009), as well as running economy (Weyand et al., 2009) as able bodied runners.

How the RSPs can be manipulated to influence the performance of athletes is an unanswered question. Hsu, Nielsen, Yack, & Shurr (1999) studied the effect of different prosthetic feet on the metabolic energy cost of walking and running. Five unilateral transtibial amputees participated in the study using three different walking feet, namely the Solid Ankle Cushion Heel (SACH®), Flex-Foot® and Re-Flex Vertical Shock Pylon (Re-Flex VSP®). Essentially, these feet differed from each other in stiffness and energy return characteristics. The researchers found that the greater the energy return characteristics, the lower the metabolic energy cost of locomotion. This effect was exaggerated as the speed of movement increased.

Since the metabolic cost of movement is of very little significance to sprint athletes, results from endurance type tests such as the VO_{2max} test does not hold much value. Therefore a test was developed to examine the neuromuscular and metabolic factors that may influence sprinting performance (Rusko, Nummela, & Mero, 1993). This maximal anaerobic running test (MART) gives insight into the capacity of the athlete to perform work anaerobically, the amount of fatigue experienced by the athlete, as well as the sprinting economy. The latter is a term that describes the speed or work rate at which an athlete reaches certain blood lactate concentrations (Nummela, Alberts, Rijntjes, Luhtanen, & Rusko, 1996) and it has been shown that the MART correlates strongly with 400 m sprint performance (Nummela, Hämäläinen, & Rusko, 2007).

Therefore, the aim of this study was to determine whether physiological and kinematic performances are altered by utilising different RSPs during MART testing in a unilateral transtibial amputee sprinter.

Methods

Athlete

A unilateral transtibial male amputee sprinter (height 178.7 cm; body fat 12.2%) was recruited for this study. The athlete competes at national level and has a 400 m personal best time of 58.06 s (T44 world record 50.61 s). The study was approved by the Stellenbosch University Ethics Committee (DESC/Grobler/2014). Before testing commenced the procedures were explained to the athlete and an informed consent form was signed.

Experimental design

The athlete was asked to complete four MARTs on a motorised treadmill using different RSPs for each test. RSPs from two different stiffness categories and from two different models (model E and X) were selected for this investigation. The category selection was based on that used by the athlete. For competition and training purposes, the athlete uses a category 5 RSP; therefore a category 4 and 6 RSP for each of the prosthetic models was tested (category 6 being the stiffer of the two according to the manufacturer). The athlete was blinded to the prosthetic that was used during a specific testing session and the four RSPs were tested in random order.

All testing was completed at the same time of day to rule out circadian variations in physiological responses. Testing was completed within one week, with 24 hours rest between tests. This was done to rule out any training effects and to minimise disruptions in the athlete's training program. During the week of testing, the athlete discontinued his regular training program. Testing took place in the first week post the major competition of the season. The athlete was asked to refrain from consuming alcohol or caffeine for at least 12 hours before testing, as well as refrain from eating or drinking two hours before the testing sessions.

Pre-test protocol

Prior to each test the athlete completed a questionnaire to assess his motivation to complete the test to the maximum of his potential. His resting blood lactate concentration was determined via finger prick blood sampling (Lactate Pro 2^{TM}, Japan). Three counter movement jumps (CMJ) were performed, using the RSP that would be used in the MART test on that specific day. Jump height was determined by Optogait beams (Microgait^{TM}, Italy). The athlete was asked to jump as high as possible, keeping his hands on his hips throughout the jump. The athlete also completed three single-leg drop jumps on both his affected leg (AL) and unaffected leg (UL) from a height of 20 cm.

Maximal anaerobic running test protocol

The athlete completed increasing increments of 1 km · h^{-1}, starting at a speed of 14 km · h^{-1} at a 5.2% gradient on a motorised treadmill (Saturn, h/p/Cosmos, Germany). These increments lasted 20 s and were followed by a recovery period of 100 s. The test was terminated when the athlete could no longer maintain the speed of the treadmill. The kinematic variables of ground contact time (t_c), flight time (t_f) and stride length (SL) were determined throughout the test (Optogait, Microgait^{TM}, Italy). Breath-by-breath gas exchange and heart rate (HR) were also continuously measured using the Quark CPET metabolic system (COSMED^{TM}, Italy). During the 100 s recovery period, the RPE score of the athlete was recorded based on the 6 – 20 Borg scale, as well as blood lactate concentration by finger prick blood sampling.

Recovery protocol

The athlete completed a 15 minute passive recovery period after the maximal speed was reached. During this time blood lactate concentration was measured immediately after, 5 min, 10 min and 15 min after the completion of the final stage. The athlete's RPE score was also noted. Furthermore, three CMJs were performed at 2.5 min, 5 min and 15 min after the completion of the final stage of the test, as described earlier. During this passive recovery period, the athlete completed a final questionnaire to assess his perception of the RSP during the running test. At the completion of the 15 min recovery period, the athlete was asked to complete three single-leg drop jumps on the AL and UL.

Athlete perception

The athlete was asked to complete a questionnaire after completion of the MART test. This questionnaire was aimed at determining the athlete's perception of the RSP. The athlete was asked to rank the comfort of the RSP during walking, submaximal speed running and maximal speed running comfort of the RSP on a scale of 1 (extremely uncomfortable) to 10 (extremely comfortable). Furthermore, the athlete was also asked to gauge his perceived effort of using the RSP on a scale of 1 (very easy) to 10 (very hard).

Data analysis

Running speed was used as a proxy for the power, expressed as oxygen demand, and as an estimate of sprinting economy (Nummela et al., 1996). This was done as the extent of the metabolic effect caused by the muscle tissue loss is unknown.

The stiffness of the AL and UL during the single leg drop jumps was calculated using the t_c and t_f measured during the jumps, as described by Dalleau, Belli, Viale, Lacour, & Bourdin (2004).

Results

Rest

Baseline values that were collected prior to each test are shown in Table 1. The athlete was similarly motivated before all the testing sessions. There was some variation in body mass (range 76.4 – 77.7 kg), however, this was not associated with the jump height variations. The mass of the RSPs were all within 0.2 kg of each other. The blood lactate concentrations in the rested state were all within the physiological range for resting values.

According to the calculations, the E_{cat4} RSP displayed the highest stiffness and X_{cat4} the lowest stiffness. The athlete reached higher drop jump heights with the affected leg (AL) with both categories of the model X. There were slight variations in drop jump height and RSP stiffness between the different RSPs in the unaffected leg (UL).

Table 1 Pre-exercise questionnaire and physical measurements for each of the test days using the RSPs E_{cat4} - X_{cat6}

	E_{cat4}	**E_{cat6}**	**X_{cat4}**	**X_{cat6}**
Body mass (kg)	76.4	77.5	77.7	76.9
RSP mass (kg)	2.9	2.8	3	2.9
Motivation (1-10)	9	10	9	10
Blood lactate concentration	0.8	1.1	0.8	0.6
CMJ (cm)	33.0	31.3	35.2	32.6
DJ_{AL} (cm)	12.2	15.0	16.7	16.6
DJ_{UL} (cm)	16.2	19.2	21.4	17.1
K_{AL} ($kN \cdot m^{-1}$)	17.24	15.96	11.23	13.03
K_{UL} ($kN \cdot m^{-1}$)	12.23	9.44	9.66	11.97

RSP, running specific prosthetic; CMJ, counter movement jump; DJ_{AL}, drop jump affected leg; DJ_{UL}, drop jump unaffected leg; K_{AL}, stiffness affected leg; K_{UL}, stiffness unaffected leg

Sub-maximal exercise

Sprint economy. Running speed, heart rate and VO_2 at fixed blood lactate concentrations of 3 mmol · l^{-1}, 5 mmol · l^{-1}, 7 mmol · l^{-1} and 10 mmol · l^{-1} were determined. The athlete's speed at 10 mmol · l^{-1} was greater with model E than with model X (Figure 1). HR values were higher at the different blood lactate concentrations with the stiffer category RSP of each model.

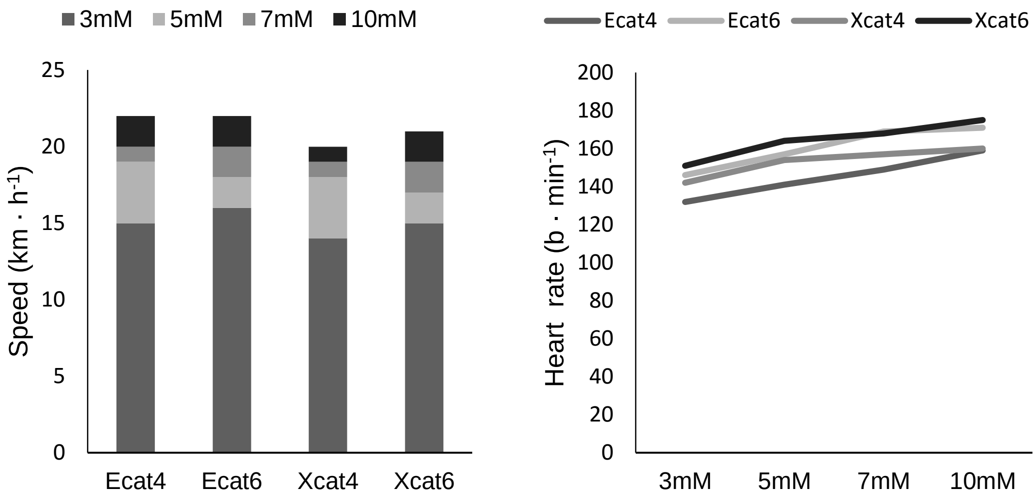

Figure 1 Speed (left) and heart rate (right) at specific blood lactate concentrations (3, 5, 7, and 10 mmol · l^{-1}) during the MART tests with different RSPs

Kinematics. The kinematic analysis revealed increases in step frequency and step length on both the AL and UL with an increase in speed (Figure 2). This result was found across all RSP conditions, except for step length in the UL while running with E_{cat6}, where the step frequency decreased from 14 km · h^{-1} to 21 km · h^{-1} due to the short step length at 14 km · h^{-1}. In both the AL and UL the variation in contact time was much larger at 14 km · h^{-1} than at 21 km · h^{-1}. In the UL, the step length and step frequency was virtually identical across the different RSP conditions at the fastest common speed (21 km · h^{-1}). Asymmetry between the AL and UL was prevalent with all the RSPs and across all speeds in both step length and step frequency. At the fastest common speed, the step length was always longer in the UL than in the AL, and the step frequency was greater in the AL than in the UL. Contact time decreased in all RSP conditions from 14 km · h^{-1} to 21 km · h^{-1}, with model E showing greater decreases in t_c than model X.

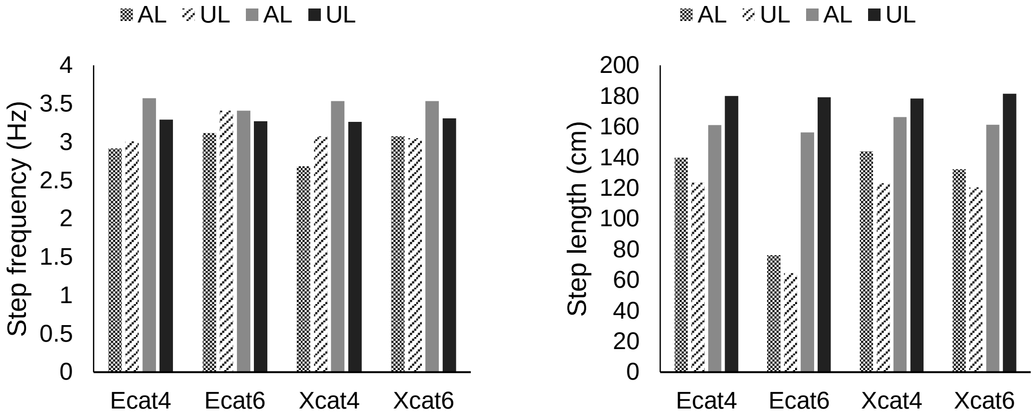

Figure 2 Step frequency (left) and step length (cm) for the affected (AL) and unaffected (UL) leg with different RSPs The textured columns indicate values at 14 km · h^{-1} and the solid columns indicate values at 21 km · h^{-1}.

Maximal exercise

Physiological variables. Different maximal speeds were obtained by the athlete with the different RSPs (E_{cat4} 24 km · h^{-1}; E_{cat6} 23 km · h^{-1}; X_{cat4} 23 km · h^{-1}; X_{cat6} 22 km · h^{-1}). For both the model E and X it was found that the [BLa] at the end of the test was higher in the softer RSP in comparison to the stiffer RSP ([BLa] difference model E = 1.8 mmol · l^{-1}; model X = 6.2 mmol · l^{-1}). This coincides with the greater percentage of fatigue, as measured with the CMJ, experienced in the softer RSPs (difference in % fatigue: model E = 10.83%; model X = 7.87%).

The inverse of this trend was found for HR and VO_2, with the stiffer RSPs resulting in higher HR and VO_2 in comparison to the softer RSPs in each RSP model (Table 2).

Table 2 Physiological measurements taken at the final stage of the MART test for each of the RSPs

	E_{cat4}	**E_{cat6}**	**X_{cat4}**	**X_{cat6}**
Speed (km · h^{-1})	24	23	23	22
[BLa] (mmol · l^{-1})	16.4	14.6	19.1	12.9
HR (beat · min^{-1})	169	178	169	177
VO_2 (ml · min^{-1})	2906.74	3124.69	3079.36	3382.23
CMJ fatigue (%)	18.18	7.35	24.43	16.56

[BLa], blood lactate concentration; HR, heart rate; VO_2, oxygen consumption; CMJ, counter movement jump

Kinematics. Although it is not possible to compare the kinematic parameters between the different RSP conditions due to the differences in the maximal speeds obtained, it is still possible to compare the asymmetry between the two legs in each case (Table 3). In all RSPs, the step frequency was greater in AL than in UL. Subsequently, the step length was longer in UL than in AL, with the difference being larger in model E. In both the model E categories, the ground contact time was longer in the AL than in UL, whereas the opposite was true for model X.

Table 3 Kinematic measurements for the affected (AL) and unaffected (UL) leg at maximal speed for each of the RSPs

	E_{cat4}		**E_{cat6}**		**X_{cat4}**		**X_{cat6}**	
	AL	**UL**	**AL**	**UL**	**AL**	**UL**	**AL**	**UL**
***f* (Hz)**	3.84	3.56	3.60	3.46	3.71	3.55	3.53	3.31
SL (cm)	169.9	192.7	163.7	184.1	171.5	181.0	161.2	181.4
t_c (s)	0.148	0.142	0.160	0.147	0.154	0.160	0.151	0.162

AL, affected leg; UL, unaffected leg; *f*, step frequency; SL, step length; t_c, contact time

Recovery

Blood lactate concentration peaked at 5 minutes post exercise in all trials, with the highest [BLa] in the E_{cat4} RSP (26 mmol · l^{-1}) and the lowest in the X_{cat6} RSP (17.7 mmol · l^{-1}). Although the [BLa] decreased until the final measurement at 15 minutes post-exercise, the values did not reach pre-exercise values yet. At the final measurement, the [BLa] in E_{cat4} RSP was still the highest (17.7 mmol · l^{-1}) and X_{cat6} was still the lowest (11.3 mmol · l^{-1}), however, the percentage change was the greatest for X_{cat4} (42%) (Table 4).

Table 4 Percentage change in the blood lactate concentration and counter movement jump measurements from the end of exercise to 15 minutes post exercise

	E_{cat4}	**E_{cat6}**	**X_{cat4}**	**X_{cat6}**
Δ [BLa] (%)	31.9	29.1	41.7	36.2
Δ CMJ (%)	7.0	5.1	17.1	7.4

∆[BLa], percentage change in blood lactate concentration; ∆CMJ, percentage change in counter movement jump

For both RSP models, a greater percentage of muscular fatigue was measured with the stiffer of the two RSPs, although after 15 minutes of recovery the athlete experienced similar amounts of muscular recovery in all but the X_{cat4} RSP, with which a greater amount of metabolic recovery was experienced (E_{cat4} 7%; E_{cat6} 5%; X_{cat4} 17%; X_{cat6} 7%).

The drop jump height on the AL was greater in the softer RSP of the two models, with X_{cat4} (least stiffness) resulting in the highest drop jump height, whereas E_{cat6} (most stiffness) resulted in the lowest drop jump height (Figure 3). The stiffness calculated from the drop resulted in a similar pattern as was determined in a previous study (Grobler, Ferreira, Vanwanseele, & Terblanche, n.d.), however, there was a large difference in these stiffness values (> 5 kN.m^{-1}).

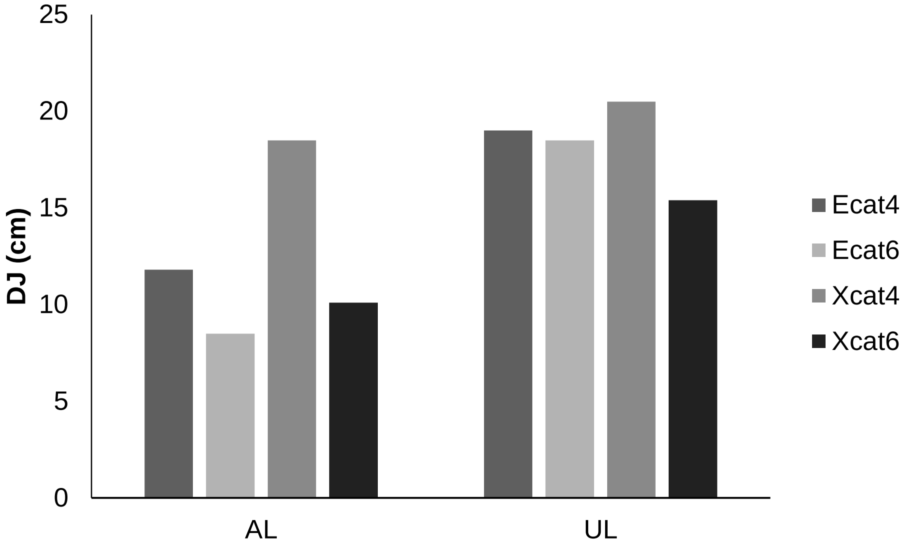

Figure 3 Drop jump height (cm) after the 15 minute recovery period with the affected (AL) and unaffected (UL) leg for each of the RSP conditions

Athlete perception

The athlete rated the stiffness of the different prosthetics similar to that determined in a previous study (Grobler et al., n.d.) (Table 5). Walking comfort was rated the lowest with the X_{cat6} RSP (7), but during jogging the stiffest of the RSPs (E_{cat6}) was found to have the lowest comfort (4). At maximal speed the X_{cat4} was rated highest (9), whereas X_{cat6} was given the lowest rating (3). The stiffest of the RSPs (E_{cat6}) resulted in the highest effort rating, however, the second highest effort rating was handed to the softest RSP (X_{cat6}).

Table 5 Results from the athlete perception questionnaire with 1 being the lowest score and 10 the highest

	E_{cat4}	E_{cat6}	X_{cat4}	X_{cat6}
Stiffness (1-10)	7	9	4	6
Walk comfort (1-10)	10	9	10	7
Jog comfort (1-10)	8	4	9	9
Maximal speed comfort (1-10)	8	6	9	3
Perceived effort (1-10)	7	10	8	4

Discussion

This study explored whether differences exist in the physiological and kinematic performance of an athlete utilizing different RSPs during a maximal anaerobic running test. The study found several differences related to the performance of this athlete and in most cases it related to the stiffness of the prosthetic in question.

The measurements taken at rest indicated that the athlete was in a similarly rested state prior to testing on the different days. The stiffness of the different RSPs used in this study was determined before (Grobler *et al.*, n.d.). According to these results the stiffness of E_{cat6} was the highest and that of X_{cat4} the lowest. Due to the recoiling nature of the carbon fibre prosthetic, the amount of energy returned is determined by the amount of loading on the prosthetic. This was evident in the pre-test CMJ where the greatest height was achieved with the softest RSP, indicating a greater ability to utilize the recoil action of the prosthetic.

The MART has been designed with the aim of determining sprinting economy. Sprinting economy is related to the metabolic workload that is attained at blood lactate concentrations of 3 mmol · L^{-1} and 10 mmol · L^{-1}. In the current study speed was used as a proxy for metabolic workload as the influence of the limb loss on the equations traditionally used to determine metabolic work is not known. It was found that the speed at both 3 mmol · L^{-1} and 10 mmol · L^{-1} was highest in the stiffest RSP and decreased as the stiffness of the RSPs decreased. In previous research it was found that at a lactate concentration of 10 mmol · L^{-1}, significant muscular fatigue becomes evident (Hirvonen, Nummela, Rusko, Rehunen, & Härkönen, 1992) which is related to the recruitment of slow twitch muscle fibres in order to maintain the speed, leading to increased ground contact times (Nummela, Vuorimaa, & Rusko, 1992).

This relationship was not found to be true for heart rate and VO_2 at these blood lactate concentrations. This may be explained by the linearity of the relationship between running speed (workload), and HR and VO_2 indicating that the workload at which the athlete reached these blood lactate concentrations influenced the HR and VO_2, rather than the stiffness of the RSP.

In the current study, the athlete reached a blood lactate concentration of 10 mmol · L^{-1} at the lowest speed (20 km · h^{-1}) with the softest RSP (X_{cat4}). At this speed, the ground contact time of the AL was also the longest in the softest RSP condition. It is possible that the lower stiffness of the prosthetic may cause a decrease in the economy of the movement. Nummela, Keranen, & Mikkelsson (2007) previously found a correlation between ground contact time and running economy, stating that both the braking forces at contact as well as the elastic response of the leg are important factors influencing running economy. The sprinting economy may also be influenced by the step frequency, as it has previously been shown that by increasing the stride frequency and decreasing the vertical displacement, therefore increasing the stiffness, the economy of movement is immediately improved (Halvorsen, Eriksson, & Gullstrand, 2012).

There are multiple kinematic solutions to running at a slow pace, however, there are less options as the speed increases. This can be seen in the variation in step length and step frequency between the different RSP conditions at 14 km · h^{-1} in comparison to 21 km · h^{-1}. Interestingly, at 21 km · h^{-1}, in the UL, the step length and step frequency was similar in all RSP conditions, indicating that the RSP condition does not seem to have an influence on the stride parameters. The AL, however, is clearly affected by the RSP stiffness. The greater the stiffness of the RSP, the higher the step frequency and the shorter the steps. This is similar to biological limbs where a positive correlation exists between the leg stiffness and stride frequency (Farley & Gonzalez, 1996). The fact that the kinematic strategy of the UL is not influenced by the RSP on the AL, could indicate that in order to improve symmetry between the two sides, the AL needs to be matched to the UL.

This asymmetry in step frequency between biological and affected legs has previously been described by Grabowski et al. (2010), however, in this study the athletes used their own RSPs, and variations between RSPs were not accounted for. From the current study, however, it seems that the symmetry in step frequency between the AL and UL improves with an increase in stiffness, whereas the symmetry for step length improves with a decrease in stiffness of the RSP. These RSPs do not mimic the function of the biological limb, which supports a previous investigation on the leg stiffness characteristics of RSPs during running (McGowan et al., 2012).

Nummela *et al.* (1996) found that athletes achieve higher maximal power outputs during a second MART compared to the first test, suggesting that there is a learning effect. Although the athlete in the current study was well accustomed to the MART protocol, having completed it various times previously, there was an increase in the maximal speed obtained over the test week indicating a strong motivational influence. Further, there was no association between the stiffness of the prosthetic and the physiological responses. The neuro-muscular fatigue induced by the MART did however seem to be influenced by the stiffness of the RSP, with the greatest stiffness inducing the least neuro-muscular fatigue. This was not related to the maximal speed obtained during the MART.

The pre-test measurements of CMJ height indicate that the greatest height was obtained with the softest RSP. However, after the running protocol, the lowest CMJ height was obtained with this same RSP, suggesting greater muscular fatigue with this RSP. It is possible that work contribution from the AL is greater in the soft RSP due to the greater ability to utilize the RSP. As the AL fatigues, the utilization of the recoil response of the RSP will decrease which could cause this large decrease in CMJ height. Alternatively, the utilization of the softer RSP could cause greater load on the UL as a compensation strategy to maintain the speed, therefore causing greater disparity between the pre and post-test CMJ measurements. This greater fatigue is also in relation to the weight difference between the RSPs, however, this is not indicated in the physiological variables (HR and [BLa]). It has been found that the addition of 0.5 kg to the foot increases the moment of inertia of the leg by 13% (Martin, 1985). This increase in inertia will have contributed to the higher levels of fatigue experienced by the athlete when running with the heavier RSP of this model.

During the recovery phase the blood lactate concentration recovered at varying tempos. Due to the passive nature of the recovery phase, the differences in blood lactate concentration were not influenced by the variation in RSP condition. The muscular recovery was, however, related to the blood lactate recovery.

A major limiting factor of the current study is the fact that only one participant was tested. However, the novel results of this case study open possibilities for further investigations into the effect of RSP stiffness on the performance of sprint athletes. In future it will also be necessary to determine how the increased stiffness influences joint kinetics as injury prevention is essential to performance. The study was also limited to treadmill running. In able-bodied sprinting it has been found that kinematic differences exist between motorized treadmill running and over-ground running (McKenna & Riches, 2007). However, all testing took place on a treadmill and the comparison between RSPs can still be drawn, however, it is not sure whether this will transfer to track running.

Conclusion

The findings of this study suggest that a stiffer RSP cause less neuromuscular fatigue during a maximal anaerobic running test. This may be attributed to the improved sprinting economy of the athlete which in turn is related to the increased step frequency. It is therefore proposed that the use of a stiffer RSP may be more beneficial for longer distance (i.e. 400 m) sprint running.

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Addendum 1

Figure 4 The two prosthetic models used in both for the testing. On the left is the model E prosthetic and on the right the model X prosthetic. (Photo by L. Grobler)

Chapter 5

Discussion

The main objective of this study was to investigate the mechanical properties of different RSPs and to determine what influence these property differences have on the biomechanics and physiology of a unilateral transtibial amputee. No study has previously investigated the link between prosthetic properties and physiological and biomechanical adaptations to these properties.

Performance progression

For a Paralympic sprinter with an amputation the RSP not only affects his/her performance, but essentially enables the athlete to run and to be competitive. It is reasonable to think that RSP's had similar ergogenic effects on Paralympic sprinters as the technical swimsuits had on Olympic swimmers, albeit not necessarily to the same extent. Thus it was expected that the effects of the advancements in RSP's over the past 20 years will be reflected in the performances of these athletes.

As stated in Chapter 2, various factors other than the technological improvements could influence the performance trends found in this study. In the past it has been shown that factors such as economical advances (18) and popularity of the sport or event (18, 28) play a significant role in performance progression. From research on women's performance progressions it has also been discovered that learning from the men's races allows for a greater rate of performance improvement (31). An increase in the popularity of any sport or event creates awareness among potential sponsors, whereas more funding assists in the professionalization of the sport, better coaching and access to the best available technology. For this reason it is essential to realise that determining the difference between purely the amputee sprinters and the able bodies will not allow for definitive conclusions regarding the influence of technological advances. However, including the differences between amputee sprinters and other classifications of Paralympic sprinters at least allows for the control of the influence of the growth in the Paralympic movement and the influence thereof on performance progression in general.

From the results in Chapter 2 it was clear that along with the growth in the Paralympic movement, the performance of these athletes improved. Where the Olympic performances over the last 20 years improved by 2.8% in the 100 m and 2.2% in the 200 m, the performances of the Paralympic classes, T12, T13 and T37, improved by between 5.8% and 8.1%, inferring that some of the factors mentioned earlier may have contributed to the performance progression. Further, when investigating the performance improvement of the amputee sprinters, it is evident that there is even greater improvement in their performances. This improvement was greater than that which was experienced in the other Paralympic classifications, indicating the influence of a factor other than the development of Paralympic sport is present.

Of the Paralympic classes used in this analysis, athletes in the T42 and T44 classes rely by far the most on technology. In the T12, T13 and T37 classes, the distinction between athletes is based solely upon the differences in their disability, however, in the T42 and T44 classes, the different technological aids (RSPs) necessary for competition increases the variability within the population. This leads to the conclusion that technological changes between 1992 and 2012 may have contributed to the performance improvement seen in these athletes. Dyer *et al*. (2015) came to a similar conclusion in their study on the progression of the 100 m performances in T44 athletes in comparison to Olympic athletes. Their study included analysis of the performances of these athlete before the inception of energy storage and release prosthetic feet in competition in 1988 (8). They found a 21% performance improvement between 1984 and 1998, which was attributed to the technological advancement of the energy storage and return foot, however, the magnitude of performance improvements between consecutive Paralympic Games' have been decreasing since this development.

Essentially a prosthetic foot or an RSP aims to return the function of the leg that was lost due to the amputation. Various studies have aimed at determining the extent to which prosthetic feet are able to do this, mainly by determining the energy efficiency and energy return of the different prosthetic feet. The biological ankle has been found to have an energy efficiency of up to 241% during running at 2.8 m.s-1 (6), whereas a study on the Cheetah RSPs (Össur, Iceland), the RSPs were found to have a 95% energy storage and return (2). This means that the energy efficiency of the RSPs is a lot less than that of a biological ankle, and it was even less in the original Flex foot® (84%) (6). Differences like these could potentially cause greater variability in the performance between athletes using different running prosthetics. The inability of the prosthetic foot to mimic the energy efficiency of the biological ankle stems from the fact that the biological ankle with the surrounding musculature and connective tissue is able to generate energy, whereas the prosthetic foot can only store and return energy.

Variability in performance can be expressed as the competition density, which gives an indication of the competitiveness of a race. In a comparison of the Olympic and Paralympic (T12, T13, T37, T42, and T44) 100 m and 200 m competition densities it was found that for the Olympic athletes it was much higher than that of the Paralympic performances, indicating that the Olympic races were much more competitive. It also shows that the variability in the athletic population in the different Paralympic classes is much greater than that of the Olympic athletic population. This may be due to the fact that the Paralympic Games is still relatively young in comparison to the Olympic Games. However, it could also be attributed to the classification system. Tweedy and Vanlandewijck (2011) found that the functional classification system used by the International Paralympic Committee poses two problems with regard to the validity of the classification of athletes. These are measurement weighting and measurement aggregation, which both influence the outcome of the classification. These systems are not evidence based and grey areas are therefore prevalent which would increase the variability between athletes' abilities within a specific class.

As stated earlier, it seems that the athletic performance is much more variable in the Paralympic classes tested in this study, and upon further investigation it was shown that the T12 and T13 classes were the least variable. This can be explained by the fact that a medical classification system is used for these classes in which the classification is based on a medical vision test (32). The T37, T42 and T44 classes, however, make use of the functional classification system. This classification system also makes use of a combined class for single (T44) and double (T43) below knee amputees, namely the T44 class (Addendum H). Along with this, the athletes within a class also varies in terms of the age at which the amputation was acquired, reasons for the amputation (congenital, traumatic or disease related amputation), lifestyle maintained before the amputation, stump length, as well as differences in the RSPs that the athletes use. These factors will all impact on the variability within this specific athletic population. Moreover, the lower competition density in the T42 class in comparison to the T44 class could be an indication of the significance of the technological influence on the performance of the athletes, as athletes in the T42 class make use of multiple technological components (blades and knees) than those in the T44 class (blades only).

It is clear that the RSPs play an important role in the performance of athletes with lower limb amputation, and therefore optimizing these prosthetic components and the interaction between the athlete and the RSP may prove to be a key determining factor in performances in years to come. In order to do so, however, more research is critical. Currently very little research is available on both the properties and mechanical characteristics of the different RSPs available, as well as on the influence of these different properties of the RSPs on the biomechanical and physiological performance of the athletes.

RSP properties

In a review by Gutfleisch (2003) it was stated that:

> *"More detailed knowledge of the biomechanical properties of prostheses will allow them to be tailored to the requirements of individual athletes and to specific applications including different speeds of locomotion."* (14)

The idea of fine tuning the prosthetic to the athlete is gaining increasingly more attention in the literature, however, limited information is still available. Prosthetics have become more complex, therefore making it more difficult to prescribe prosthetics (11) while more precise information on the differences in the characteristics or dynamic properties of the RSPs could benefit athletes and coaches in RSP selection. These types of investigations into the properties of the prosthetics themselves, in isolation from the wearer is more common in walking prosthetics, and in some cases have been referred to as amputee independent prosthetic properties (AIPP) (20).

Essentially the RSP functions as a spring when force is applied to it. For instance, when an athlete makes contact with the ground during running, the spring compresses, storing some of this kinetic energy in the form of elastic potential energy. As the body weight is then shifted over the prosthetic, the spring expands again, releasing the stored elastic potential energy in the form of kinetic energy. The amount of compression that takes place will depend on the stiffness of the prosthetic as can be seen from calculations of the spring mass model:

$$k_{leg} = \frac{vGRF}{\Delta L}$$

Equation 1 Calculation of leg stiffness where k_{leg} represents the vertical stiffness, vGRF the vertical ground reaction force and ∆L the change in leg length (22).

It has been said that due to the greater compression in softer feet, these elastic storage and return (ESR) walking prosthetic feet store more potential energy than stiffer feet (16). This principle is expected to transfer to RSPs, and therefore it is expected that the greater the compression of the prosthetic the greater the potential energy storage. It has also been found that these prosthetics display a dynamic elastic response to impulses that are applied synchronously to the natural frequency of the prosthetic, thereby increasing the energy in the system (25). Therefore, in the case of synchronous force application to the natural harmonic frequency of the prosthetic, the RSP elastic response will be enhanced and smaller amounts of force application will be necessary in order to overcome damping.

Given the scarcity in literature regarding differences between RSPs, it is reasonable to think that coaches and athletes struggle to select an RSP that is suitable to the athlete. Due to the lack of information, choices are based on the manufacturer’s recommendations and experience. As the Paralympic movement grows and these athletes become more competitive and professional, the need for scientific reasoning behind prosthetic development and selection becomes more critical. For this reason, some of the properties of two models of commercially available RSPs were determined and presented in Chapter 3. Differences between the two models of RSPs were expected, as the one RSP was specifically recommended for a short distance (Model X = 100 – 200 m) and the other a longer distance (Model E ≥ 400 m) sprint prosthetics. Further differences between the various categories were also expected as these categories relate to the stiffness of the prosthetic.

It was found that the maximal vertical ground reaction force was significantly higher in the model E prosthetic than in model X. Alongside this, the maximal compression of the different prosthetics was significantly greater in the model X prosthetic than in the model E prosthetic. Therefore, the stiffness was greater in the model E prosthetic than in the model X prosthetic. In able-bodied runners, it was found that greater stiffness in the lower limbs correlates to greater energy return (reactive power) (4). However, as stated earlier, the greater the compression of a RSP the more elastic potential energy it stores, leading to greater energy return. Due to the relationship between stiffness and sprinting performance, it was thought that the model X prosthetic, which is a dedicated short distance prosthetic, would exhibit greater stiffness than the model E prosthetic. This was, however, not the case. Laferrier and Gailey (2010) stated that there is a relationship between the posterior curvature of a RSP and the stiffness thereof. They indicated that the greater the posterior curvature of the RSP, the less stiff it is (17). This was confirmed by the results of the current study in which the model X prosthetic had a significantly greater posterior curve than the model E RSP.

The prosthetics used in this study, other than including two different models of prosthetics, also included different stiffness categories of the same model of prosthetic. These stiffness categories are determined by the prosthetic manufacturers and is accomplished by varying the carbon fibre lay-up of the RSP (9). In this study the stiffness of the prosthetic was calculated by dividing the maximal vertical ground reaction force by the maximal compression of the individual RSPs (Addendum D). Differences in the stiffness of the different categories of each of the models of RSP were observed. These stiffness categories are set up specifically to accommodate athletes of different body masses. The greater the body mass of the athlete the greater the force applied to the prosthetic while running. If the prosthetic stiffness is not sufficient, this could lead to excessive bending of the prosthetic as well as prolonged contact times, which would be detrimental to performance. With regards to RSP category selection, no reference is made to the strength or experience of the athlete, even though it has been shown that vertical ground reaction force is related to sprinting speed (33). Therefore, faster athletes (elite athletes) would exert greater forces onto the prosthetic, leading to excessive compression of the prosthetic as was seen in the current study where a statistically significant influence of weight was found in both the model E and model X RSPs. This could potentially mean that distinctions should be made in the prosthetic category prescription for novice and elite athletes as elite athletes may require stiffer prosthetics due to the greater forces applied by them.

These stiffness differences between the RSPs also cause differences in the contact times measured during the first drop in this experimental design (Chapter 3, Figure 3). Statistically significant model effects were found at 28 kg, 38 kg, and 48 kg, indicating that the contact time was longer in the model X RSP in comparison to the model E RSP. For the model E RSP, category effects were found between E_{cat3} and E_{cat4}, E_{cat5} and E_{cat6}, whereas in the model X RSP, the different categories seemed to differ more from each other. This may be due to the high stiffness in the model E RSP in comparison to the model X RSP. In the case of the model E RSP, the stiffness of the different categories may be such that the force applied in this experimental design was not sufficient to elucidate differences in the contact time of the RSPs. No differences were found between model E and model X with regards to the flight time in any of the drop conditions (28 kg, 38 kg, and 48 kg). Although these differences were found with the mechanical testing, differences may exist between these results and that found in athletes due to the differences in force application. This aspect was addressed in Chapter 4.

If it is assumed that the take-off height and the landing height of an object bouncing from the ground are the same (as in the case of this experimental design), the flight time of the bounce can be used to determine the flight height:

$$h = \frac{g \times t_f^2}{8}$$

Equation 2 *Determination of flight height from flight time where h represents the flight height, g the gravitational acceleration and t_f the flight time.*

Therefore, flight time can be used as a means to measure the performance outcome of jump tests, and in the case of this experimental setup, the performance outcome of the different RSPs in different dropping conditions. In the 28 kg drop condition, no difference was found between the model E and model X RSPs, even though differences in the ground reaction force, compression and contact time existed between these two prosthetics. In the 38 kg and 48 kg conditions, on the other hand, a statistically significant model effect existed with model X obtaining statistically significant longer flight times than model E. In this case it seems that although the ground reaction force was higher in the model E RSP, the elastic potential energy stored in the model X RSP was greater than that of the model E RSP as would be expected by the greater compression experienced in the model X. This elastic energy seems to be more efficient in creating vertical lift than the higher ground reaction force in the model E RSPs.

RSP selection

In elite sports the role of science is to assist athletes and coaches in ways of obtaining the upper hand over their opponents. In sprinting for athletes with lower limb amputations, the use of a RSP creates a special opportunity to do so, as developments in technology can aid performance, as was discussed earlier. It is however important to understand the technology and the changes that it may bring to the athlete’s performance in order to make recommendations. From the results discussed it is clear that changes in the setup of the RSPs do not have an influence on the performance of the RSP. This means that when only the performance of the prosthetic is taken into account, the RSP can be set up in any way, and therefore it can be set up to suit the athlete’s running style and perception of comfort.

It was also clear that there were significant differences between the two models of RSPs, model E and model X. However, outcomes were not always what were expected. Specifically, it was not expected that the stiffness would be greater and the contact time shorter in the longer distance RSP (model E). In Chapter 3, the possible reasoning for athletes' still using the RSPs as suggested by the manufacturers, was discussed. This related to the phase characteristics of the 100 m and 400 m (Addendum E). A large portion of the 100 m race is spent accelerating (19), while the largest portion of the 400 m is spent in the speed maintenance phase (10, 15); thus there are differences in the spatiotemporal variables, specifically contact time, between the two race distances. In a study by Coh *et al.* (2001) the contact time was measured over a 20 m track during acceleration from a crouch start (120.92 ms), as well as from a flying start (89.76 ms) (5). As would be expected the ground contact times are longer during acceleration than during maximal speed/ speed maintenance running. In the case of a uni-lateral amputee, selecting a RSP that may cause longer contact times, the model X RSP, could lead to greater symmetry between the affected and unaffected legs. Inversely, in the 400 m where the predominant part of the race is spent trying to maintain near maximal speeds, it may be more effective to use the model E prosthetic due to its greater stiffness and shorter contact times.

One important difference between a biological limb and a prosthetic limb is the inability of the prosthetic limb to modulate its stiffness according to the requirements of the different phases of a race. Therefore, although there may be benefits to using the one model over the other for a specific race distance, the decision may not suit the needs of all the phases within the race. This needs to be taken into account when selecting a prosthetic.

With regards to the stiffness of the RSPs, as suggested by the manufacturers, an increase in stiffness was found with an increase in the category. Concomitantly, differences were found between the categories of RSPs in the other outcome variables as well. Therefore the categories should be selected to suit the ability and weight of the athlete. These recommendations, however, are based solely on the mechanical characteristics as determined in Chapter 3.

Prosthetic influence on sprinting

Although the mechanical property differences were observed in the different RSPs and the different stiffness categories of the RSPs, the influence thereof on the athlete's performance is not known. The general lack of research related to RSPs along with the fact that most research are focussed on determining biomechanical and physiological dissimilarities between amputees and able-bodied runners, contributes to the little understanding we have of the influence of RSP variations on athletic performance. Within the existing literature, different RSPs are used during testing. In some of the original works, RSPs were not in existence yet, and testing was therefore completed with walking prosthetics. In most cases the participants use their own prosthetics, making it impossible to determine the influence of different prosthetics. Only one study could be found in which different RSPs were compared in two elite T44 sprinters. In testing the dynamic response of the prosthetics, it was found that the Cheetah® underperformed in comparison to the Sprint Flex® by 20 J. However, this did not translate into better performance in either athletes, and they also preferred different prosthetics (3). It may be that variations in running style could account for these differences. This would then mean that prosthetic selection should not only be based on the characteristics and performance of the prosthetic itself, but that these characteristics should also suit the athlete in order to maximise the performance of the system as a whole.

From the previous section it can be seen that variations in the performance of the model E and model X prosthetic exist and that these variations are strongly influenced by the difference in stiffness brought about by the structural dissimilarities between these two models of prosthetic. In an attempt to understand what role these variations have on athlete performance, both these prosthetic models were tested on the same athlete. Furthermore, differences were also observed in the responses of the different categories within each model of RSP. For this reason, two stiffness categories were selected to be tested. As the athlete was already accustomed to running with a model X_{cat5} RSP, the E_{cat4}, E_{cat6}, X_{cat4} and X_{cat6} RSPs were used. This allowed for not only the investigation of the influence of the model of RSP on the performance of the athlete, but also the influence of the stiffness category. As mentioned earlier, the categories as set out by the manufacturers are very broad and do not allow for distinction between the competitive level and physical capabilities of the athletes. Therefore, many athletes are using RSPs that are stiffer than what is prescribed for them by the manufactures (personal communication with athletes and coaches).

From the testing completed in the second study, it was found that the stiffness of the prosthetics used with the athlete ranged as follows: $E_{cat6} > E_{cat4} > X_{cat6} > X_{cat4}$. Therefore, the model E prosthetics were stiffer than the model X prosthetics. All testing took place within one week, with a full day of rest between testing. There were thus small variations in body mass, but from the resting blood lactate concentrations it was observed that the athlete recovered well during the rest day. RSP mass was influenced by the length of the RSP (Addendum F). This length was determined by a prosthetist in order to accommodate for the compression of the RSP in response to the athlete's body mass. For the pre-test measurements, the jump results were the best with the

X_{cat4} RSP, including the unaffected leg drop jump (DJ_{UL}). The X_{cat4} RSP was the second RSP to be tested, and therefore these results are not necessarily attributed to the rested state of the athlete. From the athlete independent testing it was found that although not statistically significant, there was a trend for flight time to increase with a decrease in stiffness. This trend is evident in the DJ_{AL} results as well, however, E_{cat4} deviated from this general trend. It should be noted that the ability of the athlete to control the motion of the RSP as well as the ability to stabilize the joints, specifically the knee joint, could influence these results. In future research, larger sample sizes should be used to determine the likely trends amongst amputees.

The maximal anaerobic running test (MART) was specifically developed to determine sprinting induced metabolic and neuromuscular fatigue (27). This test has been found to be valid and reliable (21, 26) and is also used as an indication of sprinting economy (29). Furthermore, the maximal speed obtained in this test has been found to be an accurate predictor of 400 m sprinting performance (27).

Running economy reflects the economy of movement of the athlete and the ability to conserve carbohydrates at a high running intensity (30). It is determined by the amount of oxygen needed by an athlete to cover a distance of one kilometre. A more economical runner is therefore one that needs less oxygen to cover this distance. Sprinting economy, however, is indicated as the power at specific blood lactate concentrations (29). This metabolic power relates to the speed at which the athlete is running and can be calculated as oxygen equivalents as defined by the ACSM guidelines (12). However, due to the unknown influence of the amputation on these calculations, the treadmill speed was used as an indication of the power at different blood lactate concentrations. This was possible because only intra-athlete comparisons in results were done in this analysis.

From the speed at a blood lactate concentration of 10 $mmol.l^{-1}$ it can be seen that the athlete's sprinting economy was affected by the stiffness of the prosthetic (Addendum G). The highest speed (22 $km.h^{-1}$) at 10 $mmol.l^{-1}$ was obtained in the stiffest condition (E_{cat6}), whereas the lowest speed (20 $km.h^{-1}$) at 10 $mmol.l^{-1}$ was obtained in the least stiff condition (X_{cat4}). Although a 2 $km.h^{-1}$ difference does not seem to be significant, over a 400 m sprint it could amount to a 6 second time difference, which at the 2012 Paralympic games was the difference between first and sixth place in the 400 m T44 sprint. In a study by Rusko *et al*. (1993) it was found that counter movement jump height decreased significantly after participants reached a blood lactate concentration of 10 $mmol.l^{-1}$, indicating significant neuromuscular fatigue. This would then indicate that the stiffness of the prosthetic could possibly influence the fatigue of the athlete and this could further influence the performance of the athlete. The findings of this study support this assertion as there was a greater decrease in the athlete's counter movement jump height pre and post the MART with a decrease in RSP stiffness.

Stiffness has been found to be strongly related to running speed, as stiffness increases as the running speed increases (1, 23). With RSPs, however, the stiffness of the “ankle joint” cannot be modulated. The athlete has to pick a RSP stiffness before the race and this stiffness will not change such as in biological limbs. This could potentially indicate that in order for the leg stiffness of this athlete to increase with increased running speed, the athlete will have to compensate if in fact the RSP is too soft for the specific running speed required.

In a study by McGowan *et al*. (2012) the leg stiffness between the affected leg of six unilateral and two bilateral transtibial amputees was compared to the biological legs of 12 able-bodied sprinters during an incremental test of increasing speed. They found that with the biological limbs, as has been found in previous research, the stiffness increases with an increase in running speed, whereas the opposite was true for the affected legs. This was due to the fact that the vertical ground reaction force did not increase to such an extent in the affected legs as it did in biological legs, however, the leg compression increased to a much greater extent in affected legs than in biological legs. Thus it is clear that the inability to modulate the stiffness of the prosthetic has a biomechanical influence on the athlete.

In order to compare the stride parameters, we investigated the step frequency and step length at the highest submaximal speed prevalent in all four testing sessions (21 km.h^{-1}). Due to the fact that these parameters are directly influenced by running speed, we decided not to compare them at the maximal speed as there was a discrepancy in the maximal speed obtained in the various tests. Further, we specifically chose to use step rather than stride parameters in order to distinguish not only differences in general, but also specifically in the affected and unaffected leg of this unilateral transtibial amputee.

What was interesting in these results was that at this high submaximal speed, differences were present between the different RSP conditions for both step length and step frequency in the affected leg, but not in the unaffected leg (Chapter 4, Figure 2). This would indicate that the unaffected leg does not adjust to the RSP. Step asymmetry has been found in previous studies (7), however, no study has looked at the influence of different RSPs on these asymmetries. In a study sample of six elite unilateral transtibial sprinters, a statistically significant difference in the step frequency between the two legs at a speed of 8.8 ± 1.0 m.s^{-1} was found (13). In this case the step frequency was higher in the unaffected leg, which was in contrast to the results of the current study where it was the highest in the affected leg. These step asymmetries in unilateral amputees can also be ascribed to the dynamic mechanical properties of the RSPs (25). With regards to step length, it was seen that the step length from the affected leg was the longest in the X_{cat4} condition (softest RSP). This could give some insight into why the sprinting economy with this RSP was lower than that of the other RSPs. One would expect that this longer step length may be accompanied by an increased contact time allowing for more force application time, however this was not the case (Chapter 4, Table 3).

Transfer from mechanical to biomechanical results

It was found that contact times of the RSPs were influenced by the stiffness categories as indicated by the manufacturers (Chapter 3). For the RSPs used in Chapter 4 the average contact time was longer in the cat4 RSPs in comparison to the cat6 RSPs (E_{cat6} = 0.181 s; E_{cat4} = 0.183 s; X_{cat6} = 0.198 s; X_{cat4} = 0.207 s). This trend in contact time was prevalent in the athlete’s performance at the highest common submaximal running speed (21 km.h^{-1}) except for the E_{cat6} RSP (E_{cat6} = 0.171 s; E_{cat4} = 0.161 s; X_{cat6} = 0.162 s; X_{cat4} = 0.163 s). Furthermore, in the mechanical study, it was found that the flight time increased with a decrease in stiffness indicating the ability of the RSP to store elastic energy and return it during the release phase. This characteristic difference was associated with an increased step length with decreased RSP stiffness during the MART protocol (Chapter 4, Figure 2).

In a study by Noroozi *et al*. (2012) it was found that by adapting step frequency to the natural bending modes of RSPs, athletes will enhance the dynamic response of these RSPs. In further research this group also found that the human brain is able to detect natural bending modes of RSPs (24). However, this testing was only completed by applying force to the system with two fingers. It is possible that the athlete will be able to adapt to these dynamic elastic responses during running, however, this has not been illustrated yet. Nevertheless, the current study demonstrated that the mechanical results influenced the spatiotemporal characteristics of the athlete whilst sprinting.

Study limitations

The main limiting factor of the study is the single case study design for the physiological and biomechanical testing. However, there is a strong case to be made for case studies in elite sport performance, especially pertaining to a population such as amputees where there are various external factors influencing the performance of the athlete. Therefore, including more athletes in a study of this nature also increases the number of confounding variables to deal with.

Furthermore, with regards to the athlete testing, the MART is specific to 400 m sprinting and has been found to be a very good predictor of 400 m performance. This has limited the ability to make predictions about the performance of these RSPs during shorter distance sprinting. Nevertheless, the mechanical characteristics determined in the athlete independent testing carried over into the athletic performance regarding the biomechanical and physiological variables measured. It may be possible to utilize this information, specifically with regards to the stride parameters, to make predictions regarding the influence of the prosthetics on shorter distance sprinting.

With regards to the mechanical characteristics of the RSPs, the conclusions drawn from this study are limited to the RSPs tested in the study and inferences cannot be made about other RSPs models or those from other companies. The testing was also limited in determining the horizontal force component due to limitations in the rig used for the testing, as well as the force platform used.

Future research

There is a general lack in research regarding sprinting with RSPs especially pertaining to differences between RSPs. Although this study has given insight into the mechanical properties of two models of RSPs, there are various other RSPs available and future research should include the determination of the properties of these RSPs in order to draw comparisons for RSP recommendation purposes. Furthermore, in future research determining the ground reaction forces of these different RSPs during maximal speed running may give some insight into the response of these RSPs during shorter distance sprinting. One area that is still also of concern regarding the transfer of mechanical properties to athlete performance is the stump-socket interface. Determining the influence of this interface with regards to the leg stiffness and how this may or may not be changed due to different prosthetic sockets may give some insight into injury prevention in these sprinters.

Conclusions

It is clear that technology is present to some degree in all sports and that it plays a significant role in the progression of performances in sport. Whether it is with regards to improvements in training and preparation for events such as athlete testing, measurement systems such as the timing system in athletics, or specific technology enabling the athletes to compete, such as the bicycles in cycling or the RSPs in sprinting for athletes with lower limb amputations.

With regards to sprinting with RSPs, it was found that the improvement in RSP technology was a major contributing factor in the improvement in sprinting performance between 1992 and 2012. Mechanical characteristic differences were found between two models of RSP, and these characteristic differences influenced an athlete's performance during a maximal anaerobic running test. It was found that by increasing the stiffness of the RSP, the sprinting economy is increased which was accompanied by less neuromuscular fatigue induced by the exercise.

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Addendum A

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Approval Notice

Progress Report

22-Jun-2015
Grobler, Lara L

Proposal #: DESC/Grobler/2014

Title: Characterisation of running specific prostheses and its effect on sprinting performance in two competitive athletes

Dear Miss Lara Grobler,

Your **Progress Report** received on **16-Apr-2015**, was reviewed by members of the **Research Ethics Committee: Human Research (Humanities)** via Expedited review procedures on **10-Jun-2015** and was approved.
Please note the following information about your approved research proposal:

Proposal Approval Period: **10-Jun-2015 – 09-Jun-2016**

Please take note of the general Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

Please remember to use your **proposal number** (DESC/Grobler/2014) on any documents or correspondence with the REC concerning your research proposal.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Also note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required. The Committee will then consider the continuation of the project for a further year (if necessary).

This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki and the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health). Annually a number of projects may be selected randomly for an external audit.

National Health Research Ethics Committee (NHREC) registration number REC-050411-032.

We wish you the best as you conduct your research.

If you have any questions or need further help, please contact the REC office at 218089183.

Sincerely,

Clarissa Graham
REC Coordinator
Research Ethics Committee: Human Research (Humanities)

Addendum B

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STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Characterization of running specific prostheses and its effect on sprinting performance in two competitive athletes

You are asked to participate in a research study conducted by Lara Grober (BSc Sport Science, Hons B Sport Science, M Sport Science), from the Department of Sport Science at Stellenbosch University. The results will contribute to the completion of a PhD dissertation. You were selected as a possible participant in this study because you have a unilateral transtibial amputation and compete at a national level in the 100, 200 or 400m sprint.

1. PURPOSE OF THE STUDY

The purpose of this research is to investigate the mechanical characteristics of various RSP's view to determine the optimal RSP for these athletes. The athletes' performances in response to the different RSP's will be evaluated in terms of sprinting economy and kinematic variables.

2. PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

Maximal anaerobic running test (MART)
This testing will consist of four testing sessions, each of which will be two hours long. A different RSP will be used for each of the testing sessions. All testing will take place within the space of one week. Testing will take place in the Sport Physiology lab at the Department of Sport Science, Stellenbosch University. You will be asked to refrain from eating or drinking two to three hours before the testing, as well as refrain from consuming of caffeine or alcohol 12 hours before the testing session.

You will be measured with your everyday walking leg, where after you will be weighed with the RSP in which you will be running. After this you will complete three counter movement jumps and your resting blood lactate concentration will be measured by means of finger prick blood analysis. You will complete an 8 km.h^{-1} jog on the treadmill for between five to eight minutes for warm-up. After the warm up you will run for 20 seconds at a 5.2% incline at 14 km.h^{-1}, 100 seconds rest period will be given after this interval and you will then complete another interval. Each interval will be 1 km.h^{-1} faster than the previous interval. The end of the test is when you cannot run at the given treadmill speed any more. 40 seconds into each rest period the blood lactate concentration will once again be taken.

After the completion of the test, blood lactate concentration will be measured at 2.5, 5 and 10 minutes. Jumps will also be completed directly after the test ends, as well as five and 15 minutes after the end of the test.

3. POTENTIAL RISKS AND DISCOMFORTS

You may experience some discomfort during the MART and maximal speed running tests. However, this will not be more than you would usually experience during hard training sessions. Should you have any pain or discomfort 24 hours after a testing session, you will be referred to a physiotherapist for treatment at no cost to you personally.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

This study will give you some valuable feedback on the RSP that you are using for competition, such as the effect that prolonged use has on its function and whether you should change the RSP that you are currently running with to improve your performance

The research will also be beneficial for other people who run with RSP as it will help them with RSP selection.

5. PAYMENT FOR PARTICIPATION

You will not receive any payment for participation in this study.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of allocating you a number which will be dedicated to you throughout the study. All data collected will be labeled under that specific number. The data will be stored on a personal password protected computer that will be kept in the Sport Physiology laboratory at the Department of Sport Science, Stellenbosch University. Only the researchers will have access to this computer.

During video recordings, your face will not be included in the image and you will be allowed to view the recordings at any time. Only the researchers will have access to these recordings.

With publication of these results no names or information which could identify you will be included in the publications. Further no photo’s that could identify you will be used either.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact

Principal Investigator:	Lara Grobler 021 808 2818 15028151@sun.ac.za
Supervisor:	Prof E Terblanche 021 808 2742 Et2@sun.ac.za
Co-supervisor:	Dr S Ferreira 021 808 4722 sferreira@sun.ac.za

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to me by Lara Grobler in English and I am in command of this language or it was satisfactorily translated to me. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study. I have been given a copy of this form.

____
Name of Subject/Participant

____
Name of Legal Representative (if applicable)

______________________________ ______________
Signature of Subject/Participant or Legal Representative **Date**

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to __________________ He was encouraged and given ample time to ask me any questions. This conversation was conducted in [*Afrikaans/*English]* and no translator was used.

______________________________ ______________
Signature of Investigator **Date**

Addendum C

Sportwetenskap
Sport Science
STELLENBOSCH

UNIVERSITEIT
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Sport Physiology Laboratory

RSP PERCEPTION QUESTIONNAIRE

Pre-exercise test questions:

1. How motivated are you to run at a maximal intensity today?
   Where 1 is very unmotivated and 10 is very motivated

   1 2 3 4 5 6 7 8 9 10

2. Comfort when walking with the prosthetic
   Where 1 is extremely uncomfortable and 10 is extremely comfortable

   1 2 3 4 5 6 7 8 9 10

3. How well do you expect this blade to perform in the maximal test today?
   Where 1 is very bad and 10 is very well

   1 2 3 4 5 6 7 8 9 10

Post-exercise test questions:

1. Comfort when running at a submaximal intensity
   Where 1 is extremely uncomfortable and 10 is extremely comfortable

   1 2 3 4 5 6 7 8 9 10

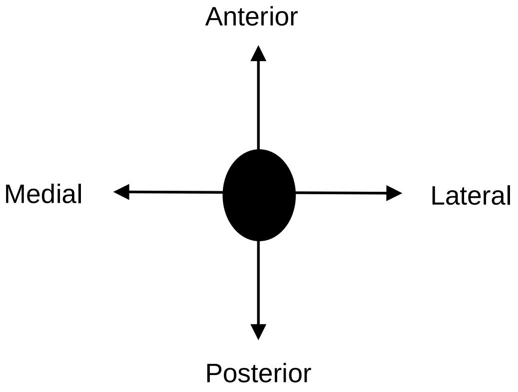
2. Comfort at max speed
   Where 1 is extremely uncomfortable and 10 is extremely comfortable

   1 2 3 4 5 6 7 8 9 10

3. Stiffness
   Where 1 is very soft and 10 is very hard

   1 2 3 4 5 6 7 8 9 10

4. Does the blade setup create the feeling of your stump being forcefully pushed into any of these directions in a uncontrollable fashion:



5. If yes to the question above, during which of the following phases of running

Slow jog		Moderate pace		Maximal speed	

6. Rate the blade in terms of your choice for a competition blade
   Where 1 is dislike very much and 10 is like very much

   1 2 3 4 5 6 7 8 9 10

7. Perceived effort in using the blade
   Where 1 is very easy and 10 is very hard

   1 2 3 4 5 6 7 8 9 10

Addendum D

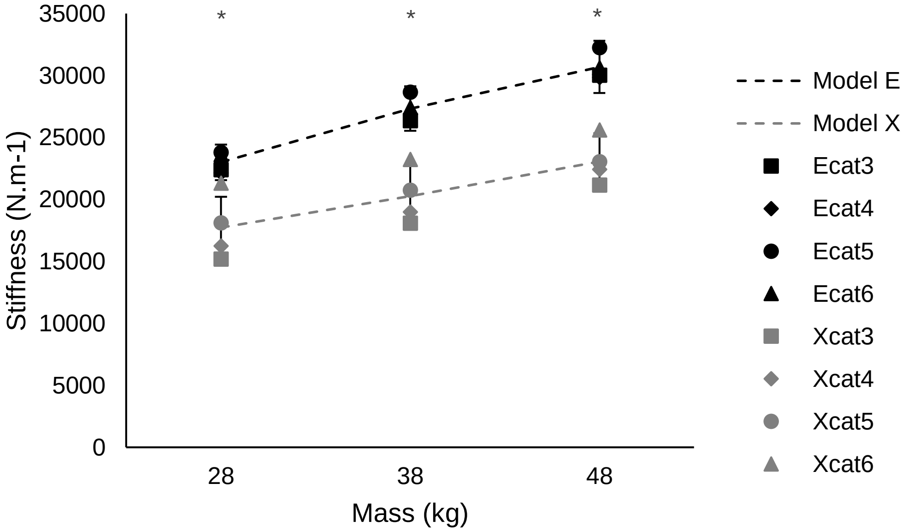


Figure 1 Mean ± SD stiffness (N.m^{-1}) measured in the two RSP models (E and X), as well as the categories of each model, using three different masses (kg). * Statistically significant difference between model E and X.

Addendum E

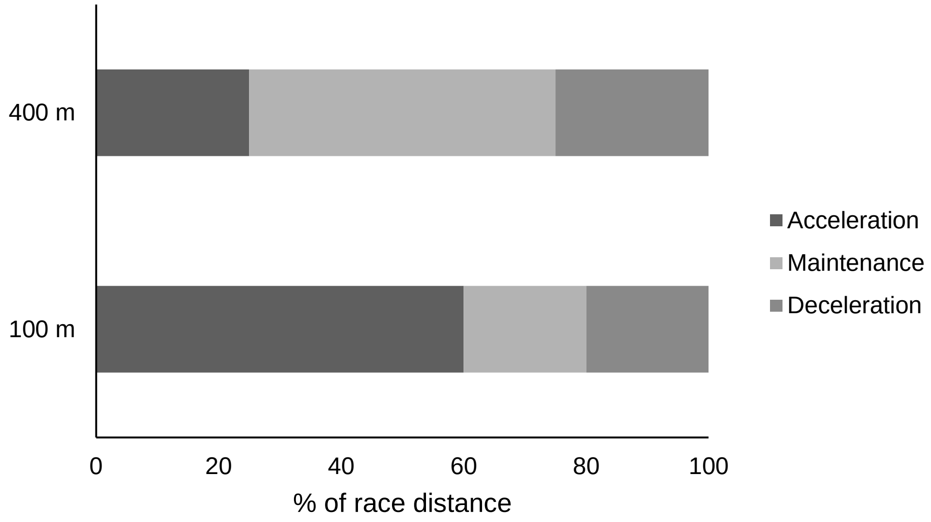


Figure 2 Indication of the % of the race distance for both the 100 m and 400 m spent in the acceleration, speed maintenance and deceleration phases.

Addendum F

Table 1 Height from the ground to the centre of the residual knee (cm) as well as the length of the carbon fibre blade component in each of the RSPs.

RSP	**Centre of knee (cm)**	**Carbon fibre (cm)**
E_{cat4}	57.6	67.4
E_{cat6}	56.5	66.4
X_{cat4}	58.8	74.0
X_{cat6}	57.5	71.9

Addendum G

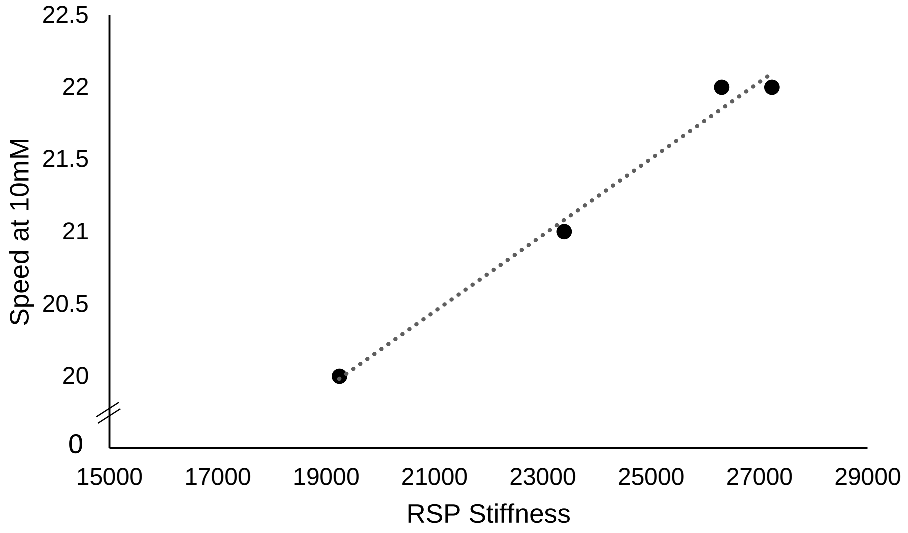


Figure 3 Relationship between the treadmill speed at a blood lactate concentration of 10 mmol.L^{-1} and the RSP stiffness as determined in Chapter 3.

Addendum H

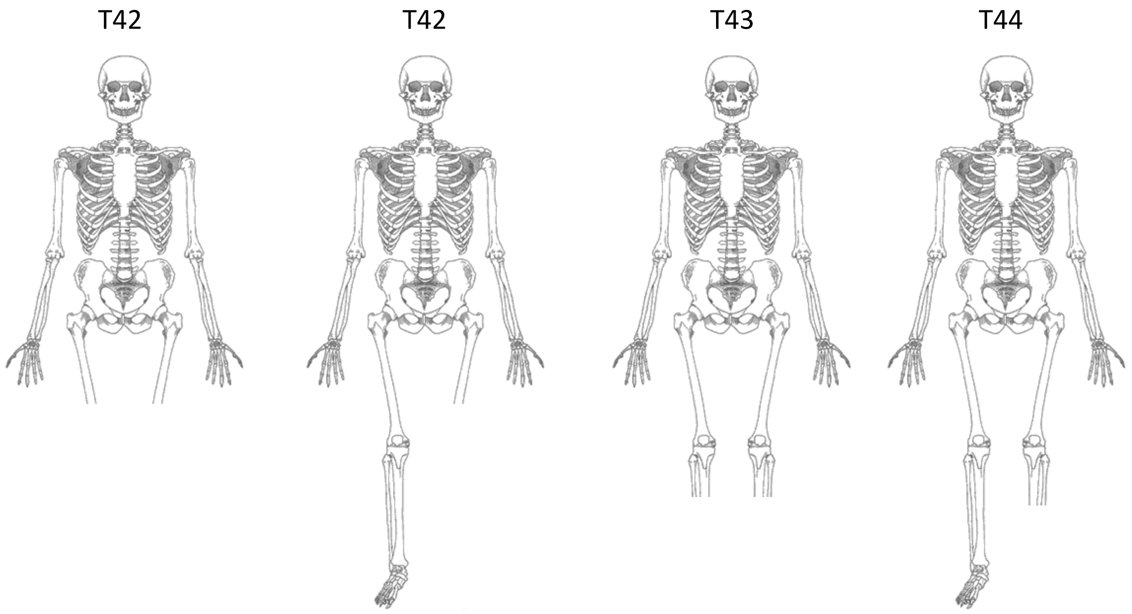


Figure 4 Figure indicating the different lower limb amputee classifications for athletic track events. Where T41 indicates a bilateral transfemoral amputee, T42 a unilateral transfemoral amputee, T43 a bilateral transtibial amputee, and T44 a unilateral transtibial amputee.