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The Biomechanical Effects of Prosthetic Arm Use on Long Jump Performance and Leg Joint Kinematics and Kinetics at Take-Off

(Dissertation submitted under the Biomechanics area)

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ABSTRACT

Following a review of current literature around the importance of arm swing in vertical and horizontal jumping and in light of the growth of Paralympic sport, the influence of prosthetic arm use on long jump performance of a T47 classified athlete was investigated, to understand whether varying arm swing would yield an immediate change in long jump performance. In two data collection sessions, one week apart, a total of 12 jumps, 6 with prosthetic and 6 without prosthetic, were completed in an indoor athletics facility. Jump performance was measured using a steel tape measure. Kinetic and kinematic data were captured using a 10 camera Vicon motion analysis system and a Kistler 9827CA force platform. Data were processed in Vicon NEXUS and Visual 3D software and variables were normalised for stance. Ankle, knee and hip joint torques and powers were calculated within Visual 3D using inverse dynamics. Mean jump performance was found to be 0.02 m better in jumps when no prosthetic arm was used. Mean joint angles were found to be similar at all joints with PR and NPR. Mean torque and power at the ankle was found to be highest with PR which would have positively affected jump performance. Knee joint torque was highest with PR but knee joint power was lower. Hip joint torque and power was lower with PR. The use of PR reduced the contribution of the knee and hip to jump performance. It is thought that there is the potential to increase long jump performance for T47 athletes by using a forearm prosthesis but that long term training would be necessary.

CHAPTER I

INTRODUCTION

1.0 INTRODUCTION

The athletic event of long jump, in its modern form, has been a constant presence in Olympic Games since 1896 (International Association of Athletics Federations, 2015). Athletes competing in long jump use an approach run to gather velocity before taking flight from a wooden take-off board, behind a foul line, marked with a plasticine strip. Should the athlete make any contact with the ground other than the sandpit beyond the foul line the jump distance would not be measured. When a successful jump is completed the distance travelled from the edge of the board to the closest mark in the sand is measured. In a typical competition, athletes would have 6 attempts to achieve the greatest jump distance possible. In elite level, able-bodied men's long jump, distances exceeding 8 metres have become common. In 2015 the top 5 athletes achieved distances between 8.38m and 8.52m. The men's world record stands at 8.95m, set by American athlete Mike Powell in 1995 (International Association of Athletics Federations, 2015).

The focus of this research lies within long jump in disability athletics. Athletics has been a part of the Paralympic Games since 1960, offering a variety of events to all impairment groups (International Paralympic Committee, 2015). Long jump is one event where the performance gap between abled-bodied and disabled athletes is beginning to shrink. Notably, in the recent IPC Athletics World Championships 2015 in Doha a German athlete, Markus Rehm, set a new World Record in the T44 impairment group of 8.40m (International Paralympic Committee, 2015). Rehm trains and competes using a prosthetic leg which has understandably been the subject of many questions about gaining advantages using high quality prosthetics. Another impairment group that may use prosthetics is the T47 classification. This impairment group is for athletes with upper limb impairments and absences (International Paralympic Committee, 2015). For T47 athletes, the World Record distance stands at 7.58m (International Paralympic Committee, 2015). In 2015 the best recorded performance by a T47 athlete was 7.19m. In the same year, there was a performance gap of 1.26 m between 1^{st} and 30^{th} place in the IPC Official World Rankings (2015). Compared to the 0.40 m performance difference between the 30 highest ranked able-bodied athletes in 2015 (International Association of Athletics Federations, 2015) there is a significant gap between the best T47 athletes and those who are placed between 15^{th} and 30^{th}. This may indicate that those athletes performing at the highest level have discovered a way of reducing the impact of their disability on performance.

There has been a great deal of research on athletic events where a prosthetic leg is required. Within sprinting and long jump, Oscar Pistorius and, most recently, Markus Rehm have inspired many questions about potential performance advantages that may or may not be brought about when an athlete uses a prosthetic leg. Perhaps the reason for the depth of research is that, among others, these athletes have become highly competitive with able-bodied athletes. There is significantly less research in to the impact of prosthetic arms on athletic performance. It is the choice of a T47 athlete whether to wear a prosthetic arm or not during training and competition. This is a variable that may prove to be influential on jumping performance in competition and is a natural area for research.

CHAPTER II
REVIEW OF LITERATURE

2.0 REVIEW OF LITERATURE

The use of arms in vertical jumping is a popular area for investigation within biomechanics. Feltner et al. (1999) investigated how lower limb joint torques were influenced by the use of an arm swing in a counter-movement jump. The participants of this study were 25 (male=14, female=11) volleyball players. Each subject performed five trials of each jump condition to provide data for analysis. All jumps were videotaped and digitised to facilitate kinetic and kinematic analysis. Jump order was randomised during data collection to limit impact of fatigue on data. Vertical jump height with use of arms was found to be 9% greater than jumps without an arm swing. 43% of increased jump height was attributed to a raised centre of mass (CM) height at the point of take-off in arm swing jumps. CM height of the body can be raised at point of take-off by extreme flexion of the shoulders which elevates the arms. The remaining performance increase was associated with effects caused by the arm swing before take-off (Feltner et al., 1999). Crucially, a greater vertical velocity was created in the propulsion phase resulting in higher vertical velocity at the instant of take-off. This, combined with an elevated CM at take-off are the only modifiable determinants of jump height (Feltner et al., 1999). If an athlete can increase both, or one of these factors, without sacrificing the other the result will be an increase in jump height because gravity is the only force that acts in the vertical direction during flight of a body. Gravity is constant and will cause an acceleration of the body towards the ground of $-9.81 m.s^{-2}$ (McGinnis, 1999). To improve jump height, it is necessary to increase vertical velocity of the body or to increase CM height at take-off. With the use of arm swing, Feltner et al. (1999) reported a 12.7% increase in CM vertical velocity at take-off compared with jumps with no arm swing. It was found that greater hip and knee torques were generated in the propulsive phase of arm swing jumps, resulting in higher take-off velocity than non-arm swing jumps. A joint torque is a type of force that creates angular motion of a body segment around an axis of rotation such as extension at the hip or knee joints. Torques are useful in developing understanding of direction of effort in movements (Robertson et al., 2014). Another commonly used variable for understanding human movement is joint power. A joint power curve can be used to display the generation and absorption of power at a joint (Robertson et al., 2014). The combination of increased CM height and vertical velocity resulted in a mean jump height increase of 0.143 m (Feltner et al., 1999). This is a clear indication of how the use of arm swing can increase performance in vertical jumping. The findings of Feltner et al. (1999) are supported by a number of studies which report similar conclusions. Lees et al. (2004) reported a vertical jump height increase of 0.086 m when using an arm swing movement. The subjects of this study were 20 athletic males with backgrounds in a variety of team and individual sports. Lees et al. (2004) showed that the findings of Feltner et al. (1999) are relevant to a range of sports performers. Lees et al. (2004) suggested that an enhanced energy storing effect was a major contributor to performance increases in arm swing jumps. It is thought that greater joint torques, caused by upwards arm swing exerting a downwards reaction force, at the hip and knee facilitated high energy storage within the musculature and tendons. When this energy was returned, in the propulsive phase benefits to jump height were seen. It is important to acknowledge that greater joint torque did not result in an increased angular velocity at the hip and knee joint. In arm swing jumps, angular joint velocity was lower than non-arm swing jumps. Therefore, in vertical jumping it may not be important to focus on increasing joint velocities when trying to improve performance. The pull theory was partially supported by the finding of Lees et al. (2004). This is a theory formulated by Harman et al. (1990). It was speculated that in the latter stages of a vertical jump, the high vertical velocity of the arms may be transferred to the trunk providing a pull effect. Lees et al. (2004) state that the pull theory becomes a factor when the arms move beyond horizontal. The net joint force at the shoulder then becomes vertical, acting to pull the body upwards. It would be interesting to investigate the effect of the pull theory when jumping for distance.

It is known that arm swing can also facilitate increases in horizontal jumping performance. Ashby & Heegaard (2002) investigated the role of arm swing in standing long jump. A passive marker motion analysis system was used to capture kinematic data as accurately and as non-invasively as possible. A force platform was used to simultaneously record ground reaction forces of trials. This study reported an increase of 21.2% in jump distance when using an arm swing compared to using no arm swing. This suggests that arm swing assists horizontal jumping more so than vertical jumping, when compared to the 9% vertical jump increase reported by Feltner et al. (1999). Ashby & Heegaard (2002) concluded that 71% of standing long jump performance increase was brought about by an increased horizontal velocity of the CM when participants used an arm swing. An average take-off angle of 38.6° was observed in arm swing jumps. This is 1.7° lower than the average take-off angle for non-arm swing jumps suggesting that there is a trade-off between vertical and horizontal velocity at take-off. It appears that increasing horizontal velocity at take-off while conserving as much vertical velocity as possible is an effective method of improving jump distance. Take-off distance (Fig. 1.) is the horizontal displacement between the take-off point and CM at take-off (Wakai & Linthorne, 2005). If this can be increased without sacrificing vertical or horizontal velocity it can benefit jump distance. Participants were able to increase take-off distance and perform more effective landing strategies in arm swing jumps, extending the toe further ahead of the CM than in non-arm swing jumps (Ashby & Heegaard, 2002) which accounted for the remaining 29% of performance increase.

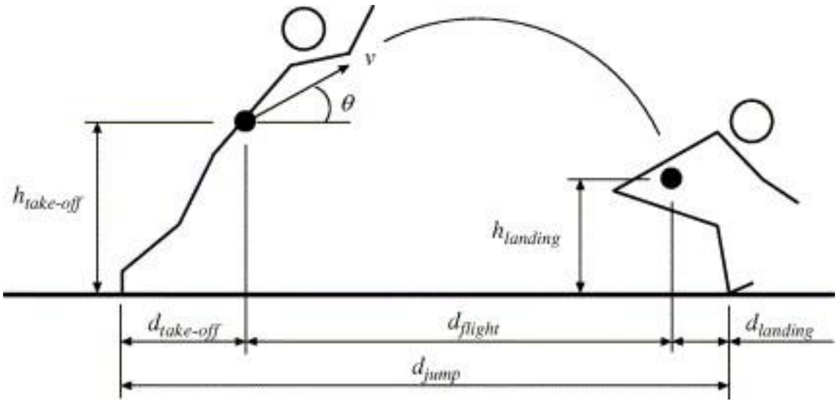

Fig. 1. Components of total jump distance in standing long jump (Wakai & Linthorne, 2005)

When an athlete uses an approach run in the long jump, vertical velocity must be generated at take-off, resulting in some loss of horizontal velocity. Achieving the optimum balance between generation of vertical velocity and loss of horizontal velocity is crucial for achieving an optimum take-off angle and a good long jump performance. It may be possible that an effective arm swing could assist an athlete in doing so. Guzman et al. (2005) investigated the optimum take-off angle for a long jump with an approach run. A high speed video camera was used to record data in this study. This minimises interference with performance but requires digitising to obtain data from the recording. Guzman et al. (2005) calculated optimum take-off angle for a long jump to be 33° but world class, male long jumpers typically exhibit take-off angles of 15-27°. Guzman et al. (2005) found that for 3 high level long jumpers the optimum take-off angle was 18-23°. This suggests that predicting optimum take-off angle using equations is somewhat unreliable and optimum take-off angles should be derived from observing elite performers. The take-off angle that produces the best performance is likely to change between athletes but should reflect the optimum angles exhibited by elite long jump athletes. Fig. 2. shows contributions to official jump distance in a full long jump.

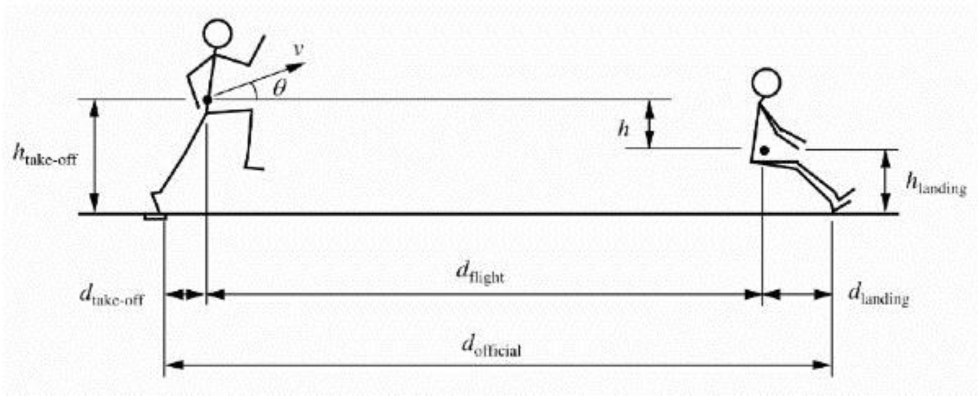

Fig. 2. Contributions to official jump distance (Guzman et al., 2005)

Flight distance is seen to be the largest contributor to official distance, with take-off distance and landing distance making up the remaining distance. Flight distance is determined by CM height at take-off, take-off angle and vertical and horizontal velocities at take-off (Guzman et al., 2005). It would be interesting to explore how modification of arm swing could influence these variables. From Fig. 2. it is seen that one arm is used to swing upwards at take-off. This is different to double arm swings as seen in investigations in countermovement and standing long jumps. This could prove to be significant for T47 athletes, especially when the affected arm is used as the swing arm. There is a strong base of research suggesting that double arm swing benefits performance in jumping, but there has been very little investigation in to modification of single arm swing and the impact on important jumping variables. The T47 impairment group provides the opportunity to modify arm length and mass by controlling the presence of a prosthesis. This allows the effect of modifying single arm swing to be quantified within one athlete, rather than comparing data from a number of athletes. It may be that a T47 athlete would experience changes in flight distance determinants as a result of prosthetic arm use.

A recent study, in which the T47 long jump world record holder participated, experimented with adding mass to the prosthetic arm. Pradon et al. (2014) captured data from long jump trials with no additional mass and with 0.3kg and 0.4kg added to the distal point of the forearm prosthesis. This study is limited by the lack of data as just 1 trial per condition was recorded and a very small familarisation period when weight was added. This provides 1 data measure per condition which could be a reliability issue and may have caused the athlete to stray from the usual jumping technique in each condition. To record kinematic data Pradon et al. (2014) applied 63 passive markers to the participant which were recorded in three-dimension (3D) using 14 optoelectronic cameras. Kinetic data was captured using floor mounted force platforms embedded in an indoor athletics track. Pradon et al. (2014)

divided the whole long jump in to 3 segments for analysis. These were impulse (take-off), flight and landing phases.

In each trial condition, vertical, anterio-posterior horizontal and medio-lateral horizontal ground reaction force components of the take-off phase were captured using the force plate. Ground contact time was also recorded. Impulse (N.s) at take-off in vertical and horizontal directions were calculated (Pradon et al., 2014). Using kinematic data, vertical and horizontal CM velocities were calculated and used to calculate direction and magnitude of the CM velocity vector at take-off. CM position at take-off was compared between conditions to assess the effect of prosthetic weight variations on take-off distance but CM height at take-off was not compared. Kinematic analysis of flight and landing technique was carried out. Analysis of the take-off phase revealed that the greatest vertical impulse, 306.0 N.s, was achieved in the trial with additional 0.3 kg. This is an increase of 7.60 N.s compared to the control jump, with no added mass, and 32.90 N.s greater than with 0.4 kg added. It is notable that despite a greater vertical impulse with 0.3kg added, the greatest vertical CM velocity at take-off was observed when no mass was added to the prosthetic. The greatest CM height in flight, 1.84 m, and jump performance, 7.01 m, were achieved. When mass was added to the prosthetic vertical CM velocity, CM height in flight, angle of take-off and jump performance decreased compared to jumps with no added mass. The results show that 0.4 kg additional mass had a negative impact on the athlete in the take-off phase but that 0.3 kg did not inhibit performance in the same phase. This is interesting as the participant now trains using 0.4 kg added to the prosthetic (Pradon et al., 2014). The athlete may perceive there to be potential benefits from using this additional mass. From the limited amount of data presented, it cannot be conclusively stated, in this study, whether changes in performance can be entirely attributed to prosthetic arm mass. The athlete was given little familarisation with each increment of mass which may have caused perturbations in technique that did not truly reflect the impact of changing the mass of the prosthesis. A greater number of trials would provide better insight in to the impact of modifying prosthetic mass. The athlete wears the prosthetic on the left arm and takes-off on the left leg. This means that the swing arm is the right and unaffected arm. Therefore adding mass to the prosthetic may serve to inhibit the performance at take-off, and have a negative impact on official jump distance.

For an athlete who uses the prosthetic arm as the swing arm at take-off there may be different changes in take-off values than those observed by Pradon at al. (2014). In such a situation it may be possible that CM height at take-off will be raised and that the upwards and forwards swing of the arm may increase the quality of the take-off impulse and contribute to the pull theory (Harman et al., 1990) as investigated by Lees et al. (2004). It would be highly enlightening to investigate the impact of entirely removing the prosthetic arm, in effect, shortening and reducing the mass of the swing arm on jump performance. It is common for athletes in the T47 classification to compete both with and without a prosthetic. This would be a simple modification for any athlete to make based on research that guides them to achieving optimal performance. Such research could help to increase performance levels for all T47 athletes and reduce the performance gap between able-bodied long jump athletes.

The take-off phase would be a natural point of focus for research as all determinants of flight distance occur in take-off. Variables such as take-off angle, leg joint torques and joint powers would be crucial to understanding how the presence of a forearm prosthetic may influence long jump performance.

The specific objective of this study is to examine if the use of a prosthetic arm can improve long jump performance through alteration of the leg joint kinetics and kinematics in the take-off phase.

CHAPTER III

METHODOLOGY

3.0 METHODOLOGY

3.1 PARTICIPANT

One British male long jumper in the T47 disability classification (Table 1) participated in this study and was asked to perform 12 long jumps in two separate sessions. The rationale and protocol of testing was made clear to the participant and informed consent was obtained prior to data collection. Ethical approval was obtained from Cardiff Metropolitan University Ethics Committee.

Table 1. Participant anthropometric measurements and best long jump records

Participant Information	
Height (m)	1.822
Body Mass with PR (kg)	71.68
Body Mass with NPR (kg)	70.96
Best Long jump with PR (m)	5.96
Best Long jump with NPR (m)	5.97

3.2 DATA COLLECTION

The subject prepared for the experiment using their own competition warm up procedure. A total of 12 jumps were recorded in two separate sessions, one week apart, consisting of six jumps each. In data collection session one, the first three trials were completed with PR and the final three trials with NPR. This order was reversed in data collection session two. Between three and five minutes recovery was ensured between trials. This reflects the typical recovery times that the participant is used to in training sessions and competitions. The recovery time was used to visually check that markers were remaining in situ on the participant. Some additional tape was applied to ensure markers did not fall off during trials.

The use of a 3D motion analysis system and a floor mounted force plate facilitated detailed 3D kinematic and kinetic data capture. All trials were performed in an indoors athletics facility equipped with horizontal jumping event sand pit and running lanes for approach runs. Kinetic data were captured on a Kistler 9287CA force platform (Kistler Instruments Ltd, Switzerland). To preserve ecological validity the force platform was covered with a secured section of artificial track surface (Mondo). The force platform was mounted, in accordance with the manufacturer's instructions, in the centre of the running lane. The track covering had a white strip of paint which was the same size as a standard long jump take-off board.

Take-off kinematics were recorded from penultimate stride before take-off to 1 m in to flight using a Vicon motion analysis system (Vicon, Oxford Metrics, UK). Ten Vicon cameras were placed around the force plate to ensure markers on the body of the participant could be tracked by at least two cameras at all times (Fig. 3). The cameras were positioned to aim down on the performance location to minimise light noise from the environment and other cameras. The camera system was dynamically calibrated using a calibration wand (Vicon, Oxford Metrics, UK) and acceptable residuals of <0.3 mm were achieved. A residual is the measure of accuracy of each camera and should be in the range of 1 to 4 mm to ensure accuracy (Vicon, Oxford Metrics, UK). A pilot test of the camera setup was used to refine camera positioning before the data collection to ensure data could be captured in a time efficient manner.

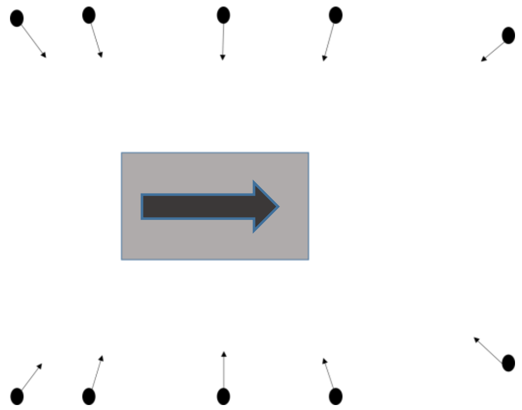

Fig. 3. Overhead view of camera location and direction of aim. Direction of athlete travel is indicated by arrow of force plate.

To allow centre of mass to be calculated from kinematic data a full body passive marker set was applied (Fig.4) after the participant had completed the majority of their warm up. The custom marker set followed the rule of at least three markers per rigid segment (Payton & Bartlett, 2008).

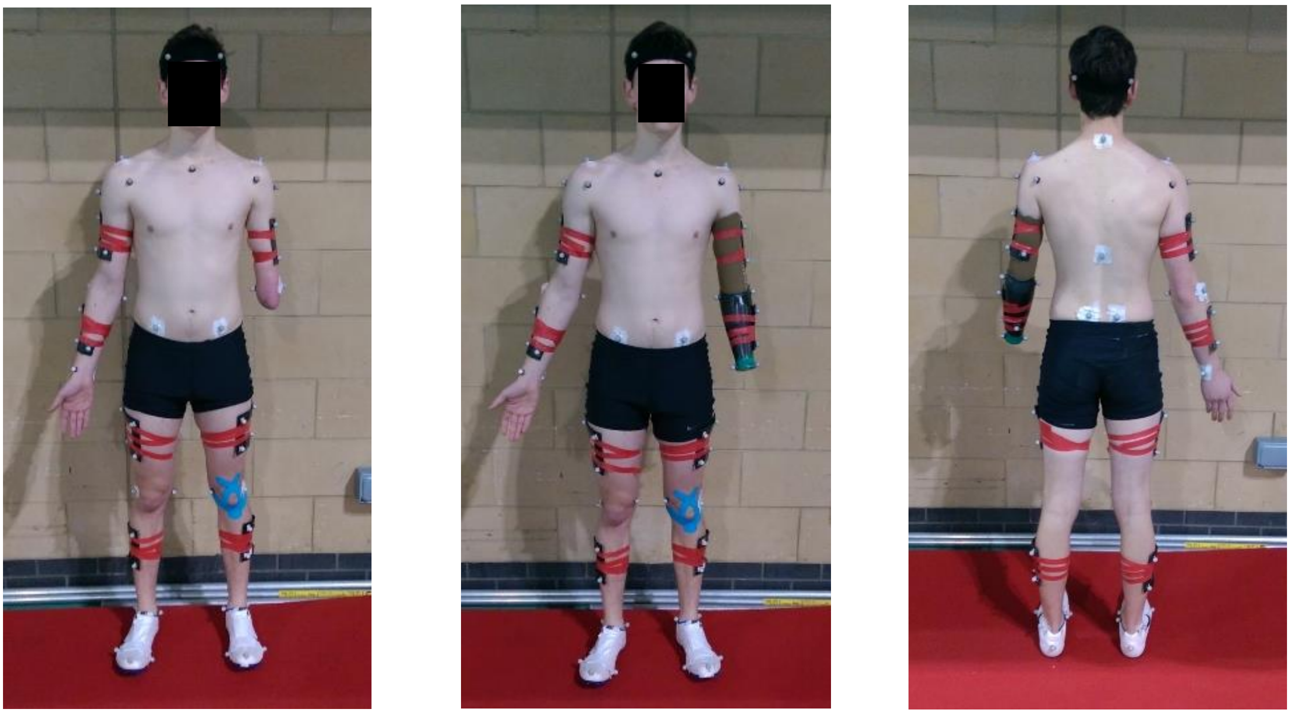

Fig. 4. Marker location on participant

Application was done efficiently to prevent the participant from becoming cold and some additional warm up after application was carried out by the participant.

A passive marker system is better suited to complex movements and would have less influence on the performance of the participant than an active marker system, while allowing a comprehensive kinematic analysis to be carried out (Payton & Bartlett, 2008). The marker set consisted of single markers and clusters of markers. Single markers are primarily used to define segments with clusters being used to track segment movement. A static calibration of the marker set was performed with the participant standing still in the capture volume. After static calibration, markers on medial joint centres were removed as tracking is mostly done using the clusters of markers placed on the limb segments, with joint centres being defined by remaining markers. Data collection was then completed as previously outlined.

3.3 DATA PROCESSING

Data were processed using Vicon Nexus 1.8.5 software (Vicon, Oxford Metrics, UK). A suitable marker model was created and saved for each of the trial conditions, PR and NPR, using the appropriate static calibration trial. The model consisted of labelled markers, defined segments and linked segments with appropriate joint types. Models were applied to data trials with markers labelled manually and segments automatically created based on the applied model. Data trials were cleaned by deleting ghost markers and by using the pattern fill function to fill gaps in marker trajectories within Vicon Nexus. Cleaned data trials were saved in C3D format and exported to Visual3D software. Using the static calibration trial a new model was created in Visual3D using the previously created Vicon Nexus model. Segments were defined using markers that were previously labelled within Vicon Nexus. Care was taken to ensure correct orientation of segments when creating models within Visual3D. A simple check was carried out using the skeleton visualisation function. Errors would appear as incorrectly orientated bones. After the model was completed, the inertia properties of the prosthetic (left forearm) were modified to be more accurate than Dempster (1955) body segment parameters used in Visual3D to calculate forearm segmental mass (Roberston et al., 2014). This was done within the options tab for left forearm where the regression equation was modified to calculate prosthetic mass, which had been determined previously in a separate weighing session.

Kinematic and kinetic data were filtered using a low pass filter function in Visual3D Pipeline at 18 hZ to eliminate noise from marker trajectories and force measurements. A separate low pass filtering was done at 120 hZ on force data only for use in external force calculations. Visual3D Pipeline commands were used to allow leg joint angles, joint torques and joint powers and force vector angle to be determined using inverse dynamics in the take-off stance phase in both trial conditions. The take-off stance phase was defined as being from the first instance of Fz rising above 20N and the first instance of Fz falling below 20N. These events were termed Touchdown (TD) and Toe-off (TO). The pipeline was saved and executed for all PR and NPR trials. Take-off variables were normalized to % of take-off stance to allow comparison of variables in the take-off phase between trial conditions. In the ankle, knee and hip 0° is full plantar flexion or extension. A positive angle in the ankle, knee and hip is dorsi flexion or flexion. It is possible that a negative joint angle may occur in the hip joint. This would occur in the event of hyper extension of the hip joint. Negative torques (N.m/kg) in the ankle, knee and hip indicate effort to create plantar flexion or extension. A negative power (W/kg) represents energy absorption while a positive power indicates energy generation. Mean joint angles, torques and powers were calculated for PR and NPR trial conditions. The angle of the force vector in the active peak was calculated manually using vertical and horizontal ground reaction force as inputs for equation 1.0 and 1.1. These calculations would allow direct comparison of variables throughout the stance phase between conditions.

$$F_{z2}+F_{y2}=C^2$$

Equation 1.0

$$\mathrm{Sin}(C/F_z)=\text{Force vector angle}/100$$

Equation 1.1

CHAPTER IV

RESULTS

4.0 RESULTS

4.1 LONG JUMP PERFORMANCE

In each jumping session, performance was greatest in which ever trial condition was tested first. In session 1, mean jump performance was 0.09 m greater with PR versus without (Table 2). In session two, mean jump performance was best in NPR jumps (Table 2).

Table 2. Session 1 and session 2 jump performance (m) with prosthetic (PR) and without prosthetic (NPR)

	Session 1 Jump Performance (m)		Session 2 Jump Performance (m)	
	PR	NPR	NPR	PR
	5.33	5.27	5.29	5.15
	5.39	NJ	5.40	5.10
	5.29	5.22	5.18	NJ
Mean	5.34	5.25	5.29	5.13

Table 3. Mean long jump performance in all PR and NPR trials

	Mean Jump Performance (m)	
	PR	NPR
	5.25 ±0.12	5.27 ±0.08
% of overall PB	88.09	88.27

Both conditions produced one no jump (NJ) each, where the athlete failed to complete the jump after take-off. These jump distances were not measured and simply recorded as NJ. Mean jump distance across all 10, out of 12, successful jumps was 0.02 m better with NPR (Table 3). Mean NPR jump distance was 88.27% of the athletes overall PB of 5.97 m. In PR jumps 88.09% of PB was achieved.

The vertical ground reaction force profiles in the stance phase exhibited the typical passive and active force peaks that are commonly seen in stance phases of walking, running and jumping. The mean angle of the force vector at the peak of the active peak was similar in both PR and NPR jumps (Table 4) and in provide an indication of the athletes’ take-off angle.

Table 4. Force vector angle in the propulsive phase of take-off

	Force Vector Angle (°)	
	PR	NPR
	21	18
	17	17
	18	17
	17	17
	17	18
Mean	18 ±2.3	17 ±1.7

4.1 LEG JOINT KINEMATICS AND KINETICS

Joint angles at the ankle, knee and hip were similar throughout take-off in both trial conditions (Fig. 5). Differences of less than 1° were found between PR and NPR ankle, knee and hip joint angles at the point of TO.

A greater dorsi-flexion (positive) joint torque was seen in the ankle joint in PR jumps in the initial 5% of stance. Immediately after the dorsi-flexion joint torque in the ankle a plantar-flexor (negative) peak was seen in both trial conditions. The larger of these negative peaks, 4.7 N.m/Kg, was seen in NPR jumps. In the final 30% of take-off stance there was a greater plantar flexor ankle joint torque in PR jumps than in NPR jumps. In the first 10% of stance a negative power of -124.7 W/Kg was seen in the ankle joint with PR. In NPR jumps this negative peak was -72.9 W/Kg (Fig. 5). This negative power is absorption of energy by the dorsi-flexors. A positive peak of 22.7 W/Kg occurred soon after the negative peak in PR jumps. In NPR jumps this peak did not become positive and NPR ankle joint power remained lower than PR ankle joint power between 10% and 90% of the stance phase (Fig. 5). Less power was lost at the ankle joint in PR jumps.

Knee joint angle showed the greatest difference between conditions. After 15% of stance phase, a greater knee flexion of between 1° and 4° throughout stance was seen in PR jumps than in NPR jumps. In the knee joint, extension torque was largest throughout the stance with PR, peaking at -8.1 N.m/Kg, except for the final 15% of stance where NPR knee torque became marginally higher (Fig. 5). The peak NPR knee extension torque was -7.5 N.m/Kg. Each trial condition exhibited knee power profiles with a large negative power in early stance followed with a period of power generation in mid-late stance. The negative power peak in the first 20% of stance was 90 W/Kg greater in PR jumps. As well as having the largest negative peak power, PR jumps also produced the largest positive peak power of 66.1 W/Kg. In NPR jumps the positive peak power was 58.9 W/Kg. In the final 75% of stance the power curve at the knee was similar in PR and NPR jumps, with small oscillations up to 60% of stance, followed by a steady decline for the remaining 40%. In PR jumps knee power at 60% of stance was 18.0 W/kg and -5.9 W/kg at 95% of stance. At these same points in NPR jumps, joint power was 11.5 W/kg and -3.8 W/Kg.

Like the knee joint, the hip displayed the most flexion in PR jumps but both PR and NPR trials ended with similar joint angles (Fig. 5). The greatest degree of hip flexion, 45° with PR and 43° with NPR, occurred at 28% of stance in both trials. Hip joint torque profiles were similar between trial conditions but torque with NPR was higher throughout most of stance. The largest extensor torque, -18.5 N.m/Kg, was seen in NPR trials. Between 40% and 65% of stance, hip joint extensor torque was consistently higher in NPR jumps than the joint torques displayed in PR jumps in this period of stance (Fig. 5). In the final 35% of stance the hip joint torque in both trial conditions was positive indicating flexion torque, despite the hip angle moving towards hyper-extension. PR trials produced a smaller flexor joint torque in late stance than NPR jumps. Negative peaks in hip joint power with PR and NPR were seen to occur in the first 25% of stance phase. The largest negative peak in hip joint power, -277.9 W/Kg, occurred in PR jumps while the largest positive peak power, 178.6 W/kg, was seen in NPR jumps (Fig. 5). In PR jumps the positive peak power was 142.1 W/Kg and was seen to occur at 30% of stance, the same point as the NPR peak power. In both PR and NPR jumps, hip joint power was negative in the final 20% of take-off stance.

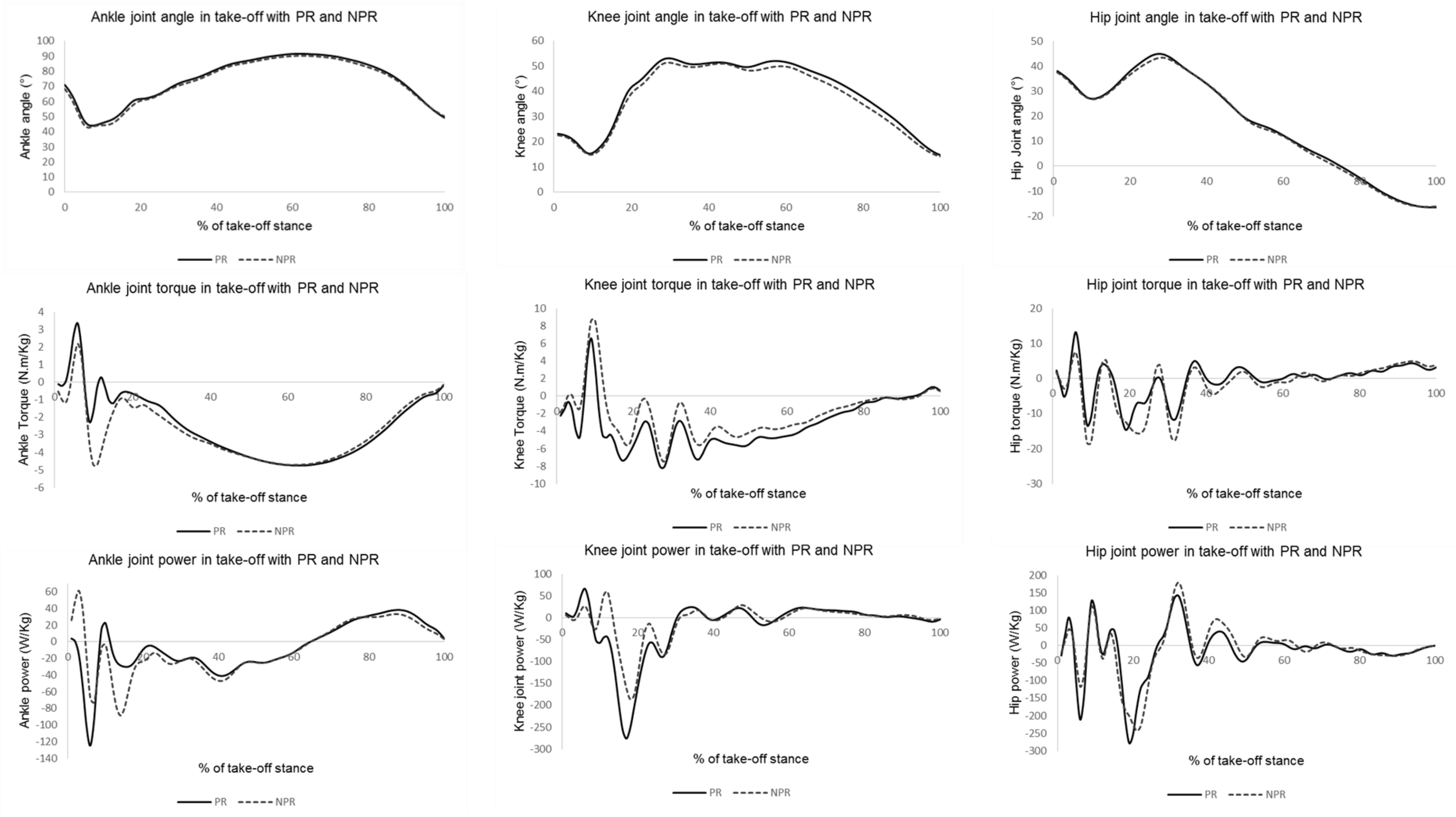

Fig. 5. Mean joint angles, torques and powers in stance for PR and NPR long jumps

CHAPTER V

DISCUSSION

5.0 DISCUSSION

This research was set out with the aim of investigating whether long jump performance could be enhanced with the use of a prosthetic forearm through alteration of the leg joint kinetics and kinematics at take-off. Across five successfully completed jumps in each trial condition, long jump performance was 0.02 m better in NPR jumps. Interestingly, in each of the data collection sessions performance decreased after the change of trial condition. This could be an indication of fatigue setting in after repeated maximal effort sprints and jumps begin to deplete Adenosine Tri-Phosphate and Phosphocreatine levels (McArdle et al., 2000). A cross over design of data collection was used to account for any training effects or fatigue between sessions. Each trial condition produced one NJ out of six jumps. It is important for an athlete to not waste competition jumps with incomplete or foul jumps. It would be a waste of energy and if too many foul jumps are done in the first three rounds of some competitions this could result in the athlete being eliminated from the competition (International Association of Athletics Federations, 2015).

The angle of the force vector created by the athlete changed by only 1°. The mean force vector angles, 18° ±2.3 with PR and 17° ±1.7 with NPR, indicate the take-off angle achieved by the athlete and are in agreement with the optimum take-off angles observed by Guzman et al. (2005). The use of PR neither assisted nor hindered the athlete achieving an optimum take-off angle but there was more variability in force vector angle with PR. An athlete would hope to achieve consistency in all aspects of performance to maximise their chances of a good overall performance. The greater variability in PR trials may be interpreted as a weakness compared to NPR trials.

Analysis of joint angles revealed few differences in PR and NPR jumps. Ankle, knee and hip joints all reached very similar angles, within 1°, at the point of TO in PR and NPR jumps. This indicates that triple extension in the take-off leg was neither augmented nor hindered by the use of PR. Chang et al. (2015) identified ankle and knee extension as key determinants of vertical jump performance. The ability to create vertical velocity and in turn vertical displacement of the body, is important for long jump performance (Guzman et al., 2005). Leg joint extension is not the only important factor to consider in jumping performance. Joint power should also be considered as important for understanding whether power is being generated or absorbed by leg joints during stance (Robertson et al., 2014).

Feltner et al. (1999) and Lees at al. (2004) concluded that joint torques were an important indicator of energy generation and storage in the musculature of the legs.

With PR and NPR, the ankle joint showed a positive joint torque in the initial 5% of the stance phase, displaying an effort at the ankle joint to lessen the rate of plantar-flexion. Despite the dorsi-flexion joint torque, peaking at 3.3 N.m/kg with PR and 2.2 N.m/kg in NPR jumps, ankle joint angle was seen to move towards plantar-flexion. The opposing changes in joint angle and joint torque produce a negative ankle joint power in both trial conditions. The ankle plantar-flexion, dorsi-flexion torque and negative power can be explained by the take-off foot positioning at TD. The power absorption in the first 5% of stance occurs in the dorsi-flexors of the ankle. From the kinematic data it was seen that the heel of the take-off foot struck the force platform (take-off board) first. This is a technical flaw that should be corrected by the athlete. Placing the take-off foot heel first is known to create a braking force (Rogers, 1999). A perfect model of performance would display a flat foot contact with the ground as this minimises braking and assists the generation of vertical velocity of the CM (Rogers, 1999). Like the dorsi-flexion ankle joint torque, ankle joint power is seen to have the greatest absorption peak in the first 5% of take-off in PR jumps. This indicates that the dorsi-flexors of the take-off leg absorb more energy in PR jumps than in NPR jumps.

In both trial conditions, between 20% and 60% of take-off, ankle joint power remained negative while a plantar-flexor torque was seen in this same period. The ankle joint angle in this period of stance was found to increase, meaning that dorsi-flexion was occurring. Because the ankle joint torque was in the plantar-flexion direction and the ankle joint angular velocity was in the dorsi-flexion direction it can be concluded that energy was being absorbed by the plantar-flexors of the ankle. The theory of enhanced energy storage and return with the use of an arm swing is somewhat supported by this study (Lees, 2004). The upward motion of the swing arm with PR may have caused a greater downwards force through the ankle joint compared to the swing arm with NPR. According to Lees (2004) an effective arm swing may augment joint torque generation and energy storage in the plantar-flexors and return of this energy in the final stages of take-off. The greater energy return from the stored energy in the plantar-flexors in PR jumps can be seen in the ankle joint power graph where in the final 15% of stance ankle joint power in approximately 5 W/Kg higher than NPR ankle power. This is evidence to suggest that the use of a prosthetic forearm results in a more effective joint torque and joint power generation at the ankle joint in take-off.

Like the ankle, the knee joint reached a similar point of extension at TO in both trials. In PR trials the knee joint was approximately 1° to 4° more flexed than in NPR jumps, indicating greater flexion, throughout take-off. This is a small difference and could be attributed to inconsistencies in marker placement on the body or slight differences in technique between trial conditions. The data collection protocol should have prevented marker placement from becoming a source of inaccuracy. Both conditions were tested in each data collection session with exactly the same lower leg marker sets. Any inaccuracy or lack of consistency would be between data collection session 1 and 2 and would therefore be present in both PR and NPR trials. It can be said with some certainty then, that the small differences in the knee joint angle are a result of the change of trial condition. It is unlikely that such a small difference would be influential on performance.

Knee joint extensor torque was calculated to have the highest magnitude throughout take-off in PR jumps. This somewhat agrees with the findings of Feltner et al. (1999) who found knee joint torque to be higher in the first two-thirds of propulsion in vertical jumps with an arm swing than jumps with no arm swing. Typically in inverse dynamical analyses a certain amount of noise or error is seen in the calculated joint torques and joint powers. Examples can be seen in sprint studies where the vertical ground reaction forces of approximately 1000 N to 1500 N are relatively low (Morin et al. 2012) and the noise of joint torque and power data (Debaere at al., 2013) is less pronounced than in this study. In this study vertical ground reaction forces of up to 4200 N were seen at the initial ground contact. The high magnitude of force in early stance, which is linked to the heel-first foot placement, is likely to have enhanced the amount of noise in this data. The relatively high knee extensor torque in PR jumps indicates that the knee extensors are working to prevent knee flexion at first TD and to extend the joint in the final 40% of stance. The higher knee flexion seen in PR jumps will directly influence the magnitude of joint torque. More joint flexion increases the length of the horizontal moment arm. So even if force application is the same in PR and NPR jumps, the longer horizontal moment arm in PR jumps would produce a larger joint torque at the knee (Robertson et al, 2014). If the work of Feltner et al. (1999) and Lees et al. (2004) is considered, it would be possible that the high knee extension torque throughout PR trials is an indication of power storage in the knee extensors and that this power storage could aid power generation at the joint in late stance.

No such enhanced power generation with PR at the knee was seen however. The main reason that similar results are not seen could be that in this research it was a modified, single arm swing that was under investigation, not a double arm swing, and that the participant was approaching the jump using a maximum effort approach run in order to jump for horizontal distance rather than a standing jump for height or standing jump for horizontal distance. There are no rules to prevent athletes from using a double arm swing in long jump competitions but it is widely accepted that a double arm swing is only advantageous to athletes competing in either high jump or triple jump competitions. Coaches believe that a double arm swing in long jumps causes loss of horizontal velocity. It is thought that the loss of horizontal velocity is due to the perturbations to normal sprint technique in the final two steps when the athlete is preparing to use a double arm swing (Freeman, 2015). Knee joint angular velocity would also have influenced the power generation at the knee (Robertson et al. 2014). From the knee joint angle figure it can be seen that knee angle displays a flat curve and changes by just 1° between 30% and 60% of stance, meaning that angular velocity is virtually zero. It is almost exactly the same point in stance when knee joint torque is at its greatest magnitude, but with no joint angular velocity power will be low. In the final 40% of stance when angular velocity of the knee increases in both trials the extensor joint torque decreases which produces a joint power that remains fairly constant. In PR and NPR trials there was an absorption of power in early stance. This is a result of the need to act against the impact force at TD that causes flexion at the knee. The large joint extensor torque at the same point in stance is another indication of the effort made to prevent knee flexion. It is important that the athlete does not allow excessive knee flexion in stance as this may inhibit long jump performance by lowering the CM height at take-off and stored energy from the eccentric contraction can be lost (Rogers, 1999). The energy stored in musculature can either be returned to assist power generation or dissipated (Stefanyshyn & Nigg, 1998). It appears that more power was absorbed and dissipated by the knee extensors in PR jumps than NPR jumps. This suggests that there may be the potential to utilise more stored energy to create power in PR jumps if the athlete was able to prevent the loss of stored energy. As the knee joint power profile in mid-late stance was similar in PR and NPR jump it can be said that neither condition enhanced long jump performance but that the potential for enhancing performance was missed in PR jumps. Specific training focussed around the approach run and take-off phase with PR may allow the athlete to make use of this potential. The athlete has been using the prosthetic for training and competition purposes for approximately 18 months so it could be said that the athlete is well practiced. But when compared to the age of the athlete, 21 years, and the length of time the athlete has been training and competing in various sports without the prosthetic, ~15 years, the degree of competency with PR comes in to question. This is something that should be considered by the athlete and coach.

In PR jumps the greatest hip joint angle was 45°.This was 2° higher than peak hip flexion in NPR jumps. The hip joint angle in PR jumps followed a similar profile to the joint angles seen throughout stance in NPR jumps. The use of PR had little impact on the hip kinematics but a greater influence on the kinetic values at the hip was seen. In the first 30% of stance, hip joint extensor torque in PR and NPR jumps showed three distinct peaks and in the remainder of stance torque magnitude was relatively low. These peaks are partly due to the high impact of TD and the noise in the force platform data associated with this. The general profile of the hip torque is similar to the findings of Stefanyshyn and Nigg (1998) who also examined joint torques in long jump performances. The high peak joint extensor torques seen with NPR suggest that the athlete was able to generate a greater extensor effort when the prosthetic was not used. This possible advantage was continued through to 65%. After this point, joint torque in both trial conditions became negative indicating an effort to slow the rate of extension at the hip joint. From observing the hip joint angle graph, it can be seen that this flexion torque in late stance did not stop the extension of the hip joint. This is a safety mechanism used by the body to bring the moving limb to rest and prevent injury from occurring in powerful movements (Jarić et al., 1995). The smaller magnitude of flexion torque in PR jumps may be the reason that hip joint angle was found to be marginally higher at the point of TO. Because of the increased hip hyper extension there may be a greater risk of injury when using PR, albeit a marginal one (Jarić et al., 1995).

Hip joint power profiles showed that in the first 25% of the take-off phase, power was primarily absorbed by the hip joint and that the most power was absorbed by the hip extensors in PR jumps. The peak negative power in PR jumps was -277.9 W/Kg. In NPR jumps the peak negative power was -243.3 W/Kg. As well as having the least power absorption, NPR jumps produced the highest power generation by the hip extensors of the two trial conditions. Peak positive power was 36.5 W/Kg higher in NPR jumps. Hip power was higher in NPR jumps for the majority of stance. There was little power generated in the second 50% of take-off in either trial condition. This makes conserving power in early stance important for this athlete. From observing power curves from various long jump athletes, it is clear that hip joint power profiles vary greatly from athlete to athlete (Stefanyshyn & Nigg, 1998) but that the power curves seen in PR and NPR trials are not usual for stance phases. It can be said that power generation at the hip joint was inhibited with the use of PR because there was larger power absorption peaks and smaller peak power generation.

This study is limited by only having one participant from which to collect data. This is due to the small number of T47 athletes who own a forearm prosthetic and were available to participate in this research. Care should be taken when considering applying the findings of this research to other T47 athletes. It would also be useful to have been able collect data from athletes in the first use of PR for long jump to fully understand the immediate effects of PR use. More data collection sessions would allow more data to be collected which may yield more information in to how PR influences long jump performance. This may have been possible if the athlete did not have a busy competition schedule to prepare for. There may be long jump performance influencing factors that occurred outside of the data capture zone. Developments in understanding of how PR affects long jump may be achieved through examining the approach run, jump and landing phases. It would have been useful to have a longer familiarisation period after the change of trial conditions than was available in this study. The performance decrease in each session may be a result of changing the structural constraints of the participant when the prosthetic is put on or removed (Newell, 1986). Typically individual structural constraints change slowly over the course of an individual life but for the participant of this study, limb length and mass can be altered immediately. The prosthetic change may have served to perturb the athlete and inhibit performance in the approach run, take-off, flight and landing of the long jump. A longer familarisation period after changing the trial condition may have prevented such a large performance decrease. This was not done as the data collection sessions were designed to replicate a competition scenario as closely as possible. Familiarisation periods were also limited because data collection in the public athletics facility was under time constraints.

Areas for future research could be the investigation of how PR use influences long jump performance among a larger population of T47 athletes or how PR use influences long jump performance when the affected arm is not the swing arm versus affected arm acting as the swing arm. It is important to note that since this research was conducted, the athlete has decided to swap from left foot take-off to right foot take-off making the swing arm the unaffected arm. This was part of an experiment decided upon by the coach and athlete after understanding of the importance of the swing arm in T47 athletes was improved. An investigation of the influence of PR use on long jump performance when the affected arm in the non-swing arm could be compared to the findings of this study. A longitudinal study of repeated data collections over the course of a full training year may address some of the limitations of this study and allow the effect of training with the prosthetic to be quantified

CHAPTER VI

CONCLUSIONS

6.0 CONCLUSIONS

The use of PR created advantages in generation of joint torque and power at the ankle and of joint torque at the knee. The high knee torque with PR did not result in higher knee power than in NPR jumps. Hip torque exhibited larger peaks with NPR than PR and hip power was seen to be lower with PR. The mean force vector angle was found to be 1° higher in PR jumps. This resulted in a mean long jump performance of 5.27 m with NPR and 5.25 m with PR. The best jump performance was achieved with NPR and the worst performance was seen in PR trials. It could be said that there is the potential to achieve a better long jump performance through joint torque and power augmentation with PR but that no immediate performance increase is likely to be seen.

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ABBREVIATIONS

Centre of mass – CM

Three-dimensions/Three-dimensional – 3D

PR – With Prosthetic

NPR – Without/No Prosthetic

TD – Touchdown

TO – Toe-off