CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

ASYMMETRY IN LOWER EXTREMITY BIOMECHANINCS DURING DUAL-LIMB LANDINGS

A thesis submitted in partial fulfillment of the requirements

For the degree of Masters of Science in Kinesiology

By

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DEDICATION

To my mom & dad,

Who has given me the unprecedented strength and motivation to pursue my dreams

To my aunt and family,

Who have helped and supported me persistently during my journey

To my girlfriend,

Who has stood by me wholeheartedly and supported me in achieving my goals

To my friends,

Who have made this process all that more enjoyable

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ABSTRACT

Asymmetry in Lower Extremity Biomechanics

during Dual-Limb Landings

By

Behrang Behjoo

Masters of Science in Kinesiology

PURPOSE: The main objective of this study was to compare energy absorption and power production between the preferred and non-preferred lower limb during a drop jump tasks.

METHODS: A total of 44 active subjects (22 males, 22 females) participated. Energy absorption and power production were measured for both lower limbs during five 0.45 m drop jumps. Two separate repeated measures ANOVAs compared energy absorption during the landing phase, and power production during the propulsion phase between the two limbs.

RESULTS: There was a main effect of limb ($P < 0.01$) where the preferred limb absorbed more energy during the landing phase. There was also a main effect for joint. Post hoc testing revealed that the hip absorbed more energy than the knee ($P < 0.01$) and the ankle ($P < 0.01$). For power production, there was a main effect of limb ($P < 0.01$), where the preferred limb produced more power than the non-preferred limb. There was also a main effect for joint ($P < 0.01$). Post hoc testing revealed that the hip produced more power than the knee ($P < 0.01$) and the ankle ($P < 0.01$). There was also a limb by joint interaction ($P < 0.01$). Post hoc testing showed that power production was greater in the preferred knee ($P < 0.01$) and ankle ($P < 0.01$), with no difference at the hip ($P = 0.95$). CONCLUSION: The findings in this study indicate asymmetrical performance of the lower limbs, and specifically that there may be a greater reliance on the preferred limb for both deceleration and propulsion behaviors. The underlying causes for these asymmetries are not clear but may be due to underlying functional asymmetries in strength and neuromuscular control. It is possible that the greater energetics and power production demands on the preferred limb could influence injury and therefore present considerations for sport training and injury rehabilitation.

INTRODUCTION

During activities of daily living, as well as sporting activities, the upper and lower extremity limbs often have dissimilar roles (e.g. preferred writing hand or, kicking leg). The reason for limb preference is not clear; however we know that they exist, as evidenced in everyday activities. Repetitions of unilateral tasks may further encourage the development of a preferred limb and has been shown to lead to different structural and functional physiological adaptations (Hellebrandt & Houtz, 1956). The literature has identified asymmetries in structural factors such as bone characteristics (Chhibber & Singh, 1970; Singh, 1970; Krahl, Michaelis, Pieper, Quack, & Montag, 1994), and muscle weight (Chibber et al. 1970), as well as functional factors such as muscle strength (Perrin, Robertson, & Ray, 1987; Alfredson, Pietilä, & Lorentzon, 1998; Fousekis, Tsepis, & Vagenas, 2010), and muscle activation (Niu, Wang, He, Fan, & Zhao, 2011). How these asymmetries affect biomechanics is not fully understood; however previous work has identified asymmetry as a potential cause for injury (Brophy, Silvers, Gonzales, & Mandelbaum, 2010; Fousekis, Tsepis, & Vagenas 2012). This theory is supported by a report that males suffered noncontact anterior cruciate ligament (ACL) injuries to the preferred (kicking) limb 74.97 % of the time, whereas 67.7% of these injuries in females occurred to the non-kicking leg (Brophy et al., 2010).

One theory for the link between asymmetry and injury is that functional adaptations resulting from unilateral tasks can lead to one limb being more resistant to loading. If this is true, then the contralateral limb may be more at risk for injury as its ability to sustain typical loading forces may be diminished compared to the preferred limb. Disproportional loading of the limbs could lead to unilateral injuries, such as noncontact ACL injuries, which encompasses approximately two-thirds of all ACL injuries (Agel, 2005). However, the role of asymmetry in biomechanics is still unclear as the majority of the biomechanics research related to ACL injury (Hoffman, Schrader, & Koceja, 1999; Decker, Torry, Wyland, Sterett, & Steadman, 2003; Yu, Lin, & Garrett, 2006; Yeow, Lee, & Goh, 2009; Gehring, Melnyk, & Gollhofer, 2009; Shultz, Schmitz, Tristch, & Montgomery, 2012) only measures data from a single limb, with the assumption that the single limb accurately represents both limbs. Whether this assumption is correct is unclear. However, investigations into lower extremity asymmetry have noted side-to-side differences in low energy tasks such as gait. In particular, several studies found that the preferred limb exhibited predominately power generation behavior, whereas the contralateral limb exhibited predominately power absorption behavior (Sadeghi, Allard, & Duhaime, 1997; Sadeghi, Allard, Prince& Labelle, 2000: Sadeghi, Sadeghi, Allard, Labelle, & Duhaime, 2001). In other words, it appears that one limb may be more effective at stabilization, whereas the other limb more effective at propulsion. While this asymmetry may be inconsequential in low energy tasks such as gait, it may potentially be more problematic when dealing with tasks that contain higher velocities and forces such as those experienced during sport activities. The lessened ability of one limb to absorb large loads during dynamic activity may place the limb at more risk for injury. However, the extent to which asymmetry affects biomechanics that may be related to injury during athletic maneuvers is unknown.

Origins of Limb Preference

Lower limb preference or "footedness" is an area that has neither been extensively researched nor defined in the field of biomechanics, but has much stronger roots in the field of neurophysiology and motor control. Most past and present biomechanics research use the term "dominance", "laterality", and "preference" interchangeably. While these terms have small, but distinct differences, they are still implying side-to-side differences. The notion of limb preference originates from the basic knowledge that two hemispheres of the brain are functionally dissimilar (Gabbard, & Hart, 1996; Hahn, 1987). It is known that the term *dominance* derives from the understanding that cerebral dominance exists in humans and that activation will differ depending on the task. It is the central nervous system (CSN) that influences which side of the brain controls a specific function. In contrast, *laterality* is defined as a peripheral influence that occurs in organisms with paired extremities such as hands and feet, where the performance of voluntary functions are superior in one limb compared to the other. Lastly, *preference* is defined as the side chosen to perform the task during a voluntary action (Touwen, 1972). Dominance and laterality will influence which side is preferred but the factors that actually drive the limb preference is not clear**.** For the purpose of this literature review, *dominance* will be used to refer to the influence of the CNS on what side of the brain plays a major role during tasks. The term *laterality* will be used to distinguish when one limb is better skilled at a specific task, and *preference* will be used to define the limb chosen to perform a task during a voluntary action.

To further understand human limb preference and asymmetry, one must look at the main theories about the origins of asymmetry. The aforementioned terms have resulted from the main theories regarding the origin of limb preference. The two main theories to which motor behaviorists subscribe are the Innate/Invariant model (Kinsbourne, 1975) and the Maturational/Equipotentiality theory (Lenneberg, 1967).

The Innate/Invariant model suggests that the preference of a lower limb may be genetically predisposed, due to functional brain asymmetries which are present at birth and persist over the life span. One study (Gentry & Gabbard, 1995) tested the innate model by studying foot preference behavior of 956 participants across six different age groups ranging from 4 years to 20 years of age. Foot preference was determined by asking participants to kick a ball. The results of this study showed that foot preference behaviors varied with age and were not permanently set. For example, between the ages of four and eight years, a significant shift toward right-footedness occurred and by the age of 11 years, a consistent foot preference was established. While they were unable to determine whether foot preference was a function of age or outside environmental factors, the researchers did attribute the changes to developmental factors and therefore rejected the Innate model and believed their results supported a more maturational perspective.

In contrast to the Innate model, the Maturational/ Equipotentiality theory suggests that preference is not genetically predetermined, but is a result of a maturational process (Lenneberg, 1967). This theory proposes that limb preference is a result of the maturational development of the hemispheres of the brain. The cerebral hemispheres are not specialized in newborns, but they become gradually specialized with age due to different age-related development of functions such as visuospatial abilities and language abilities. This theory was tested in a study that determined hand preference of 1694 participants divided into two age groups (ages 10-18 years and 19-80) (Salmaso & Longoni 1985). The older group (94.4%) had more subjects with right hand preference compared to the younger group (92.3%). While the reason for this slight difference is not clear, these results may support the theory of maturation since there was a shift of hand preference with age. However, they were unable to determine whether the larger proportion of right-handed older people was a result of age or different cultural conditions experienced by the groups.

Because our limbs often have dissimilar roles during physical activities, and repetition of the tasks may result in differences in skill between the limbs, the Maturational/Equipotentiality theory may be more plausible. As new motor skills are learned, the performance of the skill improves as more specific spatio-temporal patterns of muscle activity are learned (Provins, 1967). Task realization, feedback-mediated skill execution, and modulation of the feedback are needed for skillful task execution. Improvement in execution is achieved through repetition of a skill, due to lessened need for feedback modulation (Gottlieb, 1996). As more specific spatio-temporal patterns of muscle activity are learned, less time and space is needed and the central nervous system is able to predict musculoskeletal and environmental influences more proficiently; therefore, subsequent movements are performed more efficiently. Because we have a preferred limb during certain tasks, that limb will most likely become more skilled and have higher dependence during skill execution. This is particularly true for athletes, as they devote endless hours perfecting their respective skills. However, this may propose a problem in dual-limb tasks as now one limb may be susceptible to overloading while the other limb's ability to sustain normal loading may be diminished due to disuse.

While it is not clear which theory explains the development of limb preference, we can clearly see that individuals do prefer to use one limb over another in certain tasks. In addition, limb preference is further encouraged during daily and physical activities which may result in even greater discrepancies between limbs.

Functional and Structural Asymmetries

Asymmetry can be defined as an imbalance between bilateral limbs. They may show signs of inequality and be disproportionate to each other. This inequality could either be structural, where one is looking at the organization or design of the limb in question, or functional, where one is looking more closely at the function or purpose of the limb in question (Marieb & Mallatt, 1997).

Chhibber et al. (1970) studied the weight of muscles and bones within the lower limbs of ten cadavers and found that total weight was greater in the left lower limb in seven of the cadavers. The researchers defined the preferred limb as the heaviest limb and reported that the mean muscle weight was greater in the preferred side, where most of the difference was due to the greater mass of the sartorius, gastrocnemius, and soleus. Another investigation looked at side to side differences in the lower limbs during normal gait; the researchers found that femoral weight, foot pressure performance, and shoe wear patterns were all greater in the left leg, regardless of limb preference (Singh, 1970). The cause of these asymmetries were not identified, however the author concluded that the right and left lower limbs were not used equally.

Adaptation of tissue occurs when the stresses imposed are greater than what the tissue is accustomed (Hellebrandt et al., 1956), and this may partially explain the existence of structural and functional differences between the limbs, especially in athletes which spend countless hours perfecting unilateral skills. In an investigation measuring upper limb differences in athletes who only use one arm, (tennis players, quarterbacks, and bowlers), the researchers reported that the preferred arm had greater bone density, bone diameter, and bone length compared to the contralateral arm (Krahl et al., 1994). This was confirmed in another investigation which looked at bilateral strength differences isokinetically in 15 right-handed baseball pitchers, 15 right-handed swimmers and 15 right-handed nonathletic students. The researchers found that all groups exhibited greater peak torques in the right shoulder during extension. Additionally, internal torque acceleration energy, average power, and total work were found to be greater in the right shoulders of the pitchers (Perrin et al., 1987). All the pitchers were determined right-handed and therefore this may likely be an adaptation manifested due to the limbs not being used equally.

Another study looked at bilateral strength differences of the knee and hip in one hundred soccer players with professional experience ranging from short (5-7 years), intermediate (8-10 years), and long (>11 years). Concentric and eccentric flexion and extension torques of the knee and ankle were tested at various speeds. They found that the eccentric (at 180°/s) and concentric (at 60°/s) torque production of the knee extensors of the preferred (kicking) leg was greater than the contralateral side in the players with short and intermediate experience (Fousekis et al., 2010). This result may have been expected since soccer is sport that promotes many unilateral skills that may lead to the development of asymmetrical adaptations. In the same study, it was also reported that the preferred leg of the intermediate group was stronger than the short group during concentric knee extension at 60°/sec. The investigators attributed this to the players having a preferred limb they relied on more during unilateral tasks which would result in greater strength adaptations in the preferred limb over time. These findings are supported by another study that compared strength in the upper extremity in eleven female division one volleyball players and eleven healthy non-active females (Alfredson et al., 1998). They found more bilateral differences in strength in the elite volleyball players compared to the non-active individuals. The volleyball players exhibited greater shoulder and elbow strength in the preferred (hitting) arm compared to the non-active individuals that only demonstrated asymmetries in elbow flexion strength. The fewer asymmetries present in the non-active population may suggest that some asymmetries develop due to activities of daily living, whereas the athletes developed several more asymmetries due to their sport-activity.

These two studies provide some evidence that asymmetries in strength exist in the upper and lower extremities. While bilateral differences in maximal strength may have certain implications, it is also important to understand how the activation of the muscles may differ side-to-side. One investigation measured electromyography (EMG) activity of the tibialis anterior and lateral gastrocnemius during a drop landing task (Niu et al., 2011). They observed greater EMG amplitudes in the tibialis anterior of the non-preferred (non-kicking) leg both before and after ground contact. As the tibialis anterior is one of the main dorsiflexors, it was suggested that the greater activity was due to the non-preferred limb playing a bigger role in postural stability during a dual-limb landing task. The higher activity in the tibialis anterior was connected to lower peak dorsiflexion velocity in the ankle. This could imply that the restrained ankle motion in the non-preferred limb may have a protective effect against injury compared to the preferred limb (Niu et al., 2011).

Collectively, these studies provide evidence that structural and functional asymmetries exist in both non-active and active populations. As athletes spend much time and effort in perfecting unilateral skills, they will most likely accumulate more and greater asymmetries. This may put limbs at risk for injury if there is a discrepancy in the amount of loading that each limb can sustain. However, how exactly these asymmetries affect mechanics is not yet fully known.

Biomechanics

In both past and present research in the field of biomechanics, the majority of investigators collect data from only one limb during a bilateral task. The assumption is that the behavior of the single limb represents both limbs. In addition, investigators use different criteria to determine which limb they will measure, which further obscures the ability to compare limbs and their respective risk of injury. The most common procedures include having the participant indicate which limb they would use either to kick a ball (Yeow et al., 2009), as a support leg when kicking a ball (Shultz, et al., 2012), to hop on one foot (Yu, et al., 2006), or first to ascend a step (Hoffman, et al., 1999). Further, some studies do not indicate how they chose the testing limb (Decker et al., 2003). These examples clearly show an inconsistency in the literature in regards to defining and selecting the lower limb used for data collection, and may skew the data. The activity that is most often associated with lower limb preference is kicking a ball. Why the kicking leg is commonly classified as the preferred limb and chosen to represent both lower limbs during a dual-limb landing task is not fully clear and it may simply be due to practicality or the fact that kicking is the most common lower extremity single-limb skill.

Nevertheless, the assumption that lower extremity function is bilaterally symmetrical is evident since many studies report single limb data to represent dual-limb tasks (Hoffman et al., 1999; Decker et al., 2003; Yu et al., 2006; Yeow et al., 2009; Gehring et al., 2009; Shultz et al., 2012). If laterality is a factor during landing, the lower limbs must instead be thought of as two separate entities attempting to achieve a common goal, but the demands and efforts will differ between the two due to the existence of asymmetry. With both structural and functional differences existing, it is likely that inter-limb differences in biomechanics will also be evident. Therefore, it is prudent to consider asymmetry when investigating dual-limb tasks. There is some work which has investigated side-to-side differences during dynamic tasks (Schot, Bates, & Dufek, 1994; Cowley, Ford, Myer, Kernozek, & Hewett, 2006; Ball & Scurr, 2009; Ball & Stock, 2010; Niu et al., 2011; Edwards, Steele, Cook, Purdam, & Mcghee, 2012; Pappas & Carper, 2012; Bates, Ford, Myer, & Hewett, 2013). However, these studies looked at biomechanical variables separately (e.g. ground reaction forces or joint motion) so we still do not have a full understanding of how limb preference may manifest itself in biomechanical asymmetries as a comprehensive measurement has not need used. But we can still learn from these studies.

Ground Reaction Forces (GRF)

The large ground reaction forces or impact forces absorbed during landing have been directly linked to acute and chronic joint injuries (Boden, Griffin, & Garrett, 2000;

Boden, Sheehan, Torg, & Hewett, 2010). For that reason, researchers have observed GRF as an inference into the magnitude of joint loading. The results have been mixed, which might be attributed to differences in drop height and task (i.e. terminal vs. non-terminal).

During terminal drop landing tasks, vertical ground reaction force asymmetries of 12.8 % have been documented when landing from a 0.50 m height (Schot et al.,1994). Likewise, another study observed greater inter-limb differences in peak vGRF during the second (terminal) landing of a 0.31 m drop jump landing (Bates, Ford, Myer, & Hewett, 2013). Unfortunately, both studies did not determine a preferred leg and therefore no directional values were reported. In contrast, other work (Niu et al., 2011) reported no differences in peak vGRF, anterior-posterior GRF, or medial-lateral GRF during drop landings from three different heights of 0.32 m, 0.52 m, and 0.72 m.

During sport events, most landing tasks are non-terminal in nature, meaning that after landing it is very common to perform a subsequent movement, such as a jump or a sprint. A non-terminal landing task consists of deceleration followed by a change of direction, and is a more accurate model of an actual athletic movement. A landing task integrated with a succeeding movement may be more representative of the mechanics of a dual-limb landing during an athletic event. Therefore a drop jump would be more representative of an athletic maneuver compared to a drop landing.

However, in the research that has used a non-terminal task (i.e. landing followed by an explosive movement), the findings are equally mixed. Nonetheless, it is noted that inter-limb differences in vGRF have only been observed at low drop heights. An investigation of female high school basketball and soccer players (Cowley et al., 2006) showed that the non-preferred (non-kicking) limb, experienced greater vGRF for both during a 31 cm drop jump. Similarly, another study (Edwards et al., 2012), reported that the non-preferred (non-kicking) limb also experienced a larger peak vGRF during the vertical, but not the horizontal landing phase of stop-jump task. Ball et al. (2010) conducted a study on bilateral differences of three different drop jump heights (20cm, 40cm, and 60cm); they found that the peak vGRF was larger for the right limb during the drop height of 20cm, but no differences were found at drop heights of 40cm and 60cm. However, the authors point out that the results may have been biased because they asked the subjects to step off the box with the right leg for each trial. Because drop jumps were performed from such a low height (20cm), it is likely that the short drop time is insufficient for subjects to become bilaterally coordinated to achieve simultaneous ground contact. They suggested that 40 cm is a more acceptable value for drop height as it better represents the average vertical jump. In support of this premise, in another study by the same group (Ball & Scurr, 2009), subjects were asked to step off a 40 cm box with their right foot and perform a bounce jump (land and immediately perform a maximal vertical jump with minimum time on the ground), they saw no inter-limb differences in peak vGRF. This minimization of contact time discourages knee and hip flexion by manipulating ground contact time during landing. It is unknown whether differences in vGRF would have existed during a more natural jumping maneuver.

As the results have been mixed, it is unclear whether ground reaction forces are different between limbs. The conflicting results are likely due to testing procedure, drop height, jumping technique, subject population, and familiarization with the task. However, it should be noted that ground reaction force itself does not necessarily translate to joint loading. Instead, joint loading is a function of actual joint forces and motion.

Hip Joint Kinematics

In an investigation into kinematic asymmetries during a stop jump task, Edwards et al. (2012) used a stop-jump landing and reported greater hip flexion angle and velocity, and hip abduction at initial ground contact (IC) in the non-preferred (non-kicking) limb during the vertical landing phase of a stop jump. During the point of time of peak vGRF the non-preferred leg still exhibited greater hip flexion angle, but no significant difference in hip abduction angle was present. Moreover, the preferred lower limb exhibited greater hip external rotation during the entire vertical landing phase. This agrees with more recent research (Bates et al., 2013) which reported greater mean right hip external angle during both the first and second landing of a drop jump from a height of 31 cm. A separate study (Pappas & Carper, 2012) also reported asymmetry in hip abduction angle during both a forward jump landing and a drop landing. Unfortunately, this study reported only absolute differences and not separate limb kinematics therefore it cannot be determined which limb exhibited more abduction.

Knee Joint Kinematics

Edwards et al. (2012) also reported that during the horizontal and vertical landing phases of a stop jump the non-preferred (non-kicking) limb landed in a greater knee flexion angle at IC, however this difference was not seen at the time of peak vGRF for any of the landings. They also reported a greater knee moment in the preferred limb during the horizontal landing phase. Furthermore, during both landing phases, knee external rotation angle was found to be greater in the preferred (kicking) limb during the entire landing phase. Conversely a different study (Bates et al., 2013) found no differences in knee angles during landing from drop jump; however a greater right knee external moment was reported. Asymmetry in knee valgus angle during forward jump landings has also been reported in past research but unfortunately no directional data (Pappas et al., 2012). As greater knee valgus angle has been directly linked to ACL injuries, and ACL injuries occur unilaterally (Agel, 2005), it is possible that these asymmetries at the knee are linked to injury.

Ankle Joint Kinematics

Continuing down to the more distal joints, Edwards at al. (2012) reported that during the vertical landing phase of the stop jump, the preferred (kicking) limb displayed greater forefoot abduction at the time of peak vGRF, decreased ankle dorsiflexion velocity at IC, and increased ankle inversion velocity at peak vGRF. They also noted greater forefoot abduction joint velocity in the preferred limb during peak vGRF of the horizontal landing phase. In contrast, Niu et al. (2011) found that there were no differences in the angular displacements of the ankle during a drop-landing task, which does support (Pappas et al., 2012)**.** However they did report greater, peak dorsiflexion and abduction joint velocities in the preferred limb (Niu, et al., 2011).

Overall, the studies which have investigated asymmetries in lower extremity biomechanics provide some preliminary evidence that side-to-side differences are present during jumping and landing activities, however the existing studies investigated ground reaction forces, kinematics, and kinetics separately.

Energetics

Many researchers acknowledge that it is important to consider combining the significant kinetic between-limb differences with the kinematic differences when investigating possible mechanics underlying unilateral and bilateral knee joint injuries during dual-limb tasks. It seems that a more comprehensive biomechanical measurement is needed to fully describe lower limb asymmetries during landing. An assessment of joint energetics may be a better option since this measurement involves investigation of the joint powers (a function of joint kinetics and angular velocities) to display a more comprehensive view of the mechanics, and also provide an insight on how the multiple joints of the lower extremity act in concert to dissipate external loads (Decker et al., 2003). During landing, kinetic energy is absorbed through lower extremity eccentric muscle actions which dissipate this kinetic energy. Absorption of energy by active muscle contraction is thought to be safer than absorbing it through the passive tissues such as cartilage, ligaments, and bones (Devita & Skelly, 1992). More energy absorbed by the passive structures has been linked to both acute and chronic injuries of cartilage ligament, and bone (Boden, et al., 2000; Zhang, Bates, & Dufek, 2000).

Previous studies have reported energetics in their comparisons of sex (Decker et al., 2003), landing height (Yeow et al., 2009; Zhang, et al., 2000), landing task (Shultz et al., 2012; Yeow et al., 2009; Yeow, Lee, & Goh, 2011), and landing stiffness (DeVita & Skelly, 1992) to gain more understanding of the factors that influence lower extremity contributions to energy dissipation during a landing task. To our knowledge, no research to date has compared energetics between the two lower limbs during a non-terminal landing task such as a drop jump. However, there have been a few studies investigating energy differences during gait.

Several studies have confirmed that the limbs have different roles during gait (Sadeghi et al., 1997; Sadeghi, et. al 2000; Sadeghi et al., 2001;), and proposed that asymmetry in energetics was present due to different contributions of the lower limbs in executing out propulsion and control tasks. Sadeghi et al. (2000) suggested that symmetrical behavior in the lower limbs during gait has always been assumed for simplicity; however, the asymmetry observed during gait seemed to reflect a functional difference between the limbs that is influenced by laterality. This would imply that the lower limbs are differently skilled in the tasks occurring during normal gait (i.e. stabilization and propulsion).

One study (Sadeghi et al., 1997) reported that the preferred (kicking leg) hip generated greater positive sagittal power throughout the stance phase, which is associated with energy generation. Another study (Sadeghi et al. 2001) confirmed this and also reported that the majority of the transverse and frontal powers of the non-preferred hip and knee joints were negative, which indicates energy absorption. This provides some evidence that the limbs have different roles during gait, which may be acceptable for a stable, slow velocity movement but potentially more problematic when dealing with the higher velocities and forces experienced during high energy tasks such as athletic maneuvers.

Athletic maneuvers are often non-terminal tasks and are therefore followed by another dynamic movement, such as a sprint or an additional jump. To avoid a great delay between the sequential movements it could be hypothesized that the body prepares for the next movement while in transition. A possibly strategy of achieving this would be by distributing the tasks asymmetrically between the two lower limbs. Bilateral differences could then be seen and this offers the possibility that one lower limb may be more efficient in the task at hand which includes energy absorption (deceleration and stabilization), while the other limb focuses on the succeeding movement which includes power generation (propulsion). This would surely affect the events experienced by the two lower limbs during a dual-limb landing task and would be of great interest. As higher ground reaction forces and velocities place greater loads on the joints and have been linked to injury (Boden et al., 2000), an asymmetry which leaves one limb less resistant to loading could be potentially dangerous. Therefore, a comprehensive, bilateral measurement of lower extremity is needed.

Conclusion

During daily activities, our limbs often have dissimilar roles, and the preference of one limb over the other is often very prevalent. The reason for our limb preference is not clear; however the daily and physical activities limbs endure on a regular basis may amount to different adaptations taken by respective limb. Tissue will respond to stimulus of greater stress and the specific nature of the stress produces its own specific response and adaptations (Hellebrandt et al., 1956) and this holds especially true for athletes who spend endless hours perfecting their respective skills. Asymmetry has been linked to injury (Brophy et al., 2010; Fousekis et al., 2012) and may lead to a diminished ability of one limb's ability to resist loading.

The literature is somewhat inconsistent in its ability to verify lower limb asymmetry and the individual roles of each limb. Specifically, it is unclear whether ground reaction forces and kinematics differ between limbs. These inconsistencies have been primarily due to methodological issues such as task selection and measurement outcomes. What has become clearer is that a comprehensive measurement of lower limb biomechanics during a sport-specific task is needed.

PURPOSE AND HYPOTHESES

The purpose of this study was to investigate asymmetry in lower extremity energetics during a non-terminal bilateral drop jump landing task. Based on previous literature, it was hypothesized that 1) asymmetry in energetics would be evident during the non-terminal drop jump landing task and 2) the preferred limb (defined as the limb used to kick a ball) would exhibit greater power generation behavior, whereas the non-preferred limb would exhibit greater power absorption behavior.

METHODS

Participants

College aged participants (males and females aged 18-30 years old) who were experienced in, and regularly participate (at least 3x/week) in athletic activities which include jumping, landing, cutting, and rapid decelerations (basketball, soccer, volleyball, lacrosse, etc.). The participants could not exceed a body mass index (weight/height^2) equal to or greater than 28 kg/m^2. Participants that have had previous injuries to the ligaments in the knee, or any foot, ankle, leg, or hip pain and/or dysfunction affecting movement patterns were excluded from the research. Limb preference was established by asking the participant which foot they would use to kick a ball for maximal distance.

Instrumentation

While wearing compression shorts and running shoes, subjects were instrumented with a total of 55 reflective markers. Calibration markers were placed bilaterally on the acromion process, iliac crest, superior iliac spine, greater trochanter, medial and lateral knee, medial and lateral ankle, and the 1st and 5th metatarsal heads. Clusters of four markers were placed on top-side of the feet, shanks, thighs, and trunk, and a cluster of three markers on the sacrum. Kinematics were measured with a 6-camera Qualysis motion capture system at 240 Hz. Kinetics were measured with two separate Kistler force plates (Type 9286A and Type 9286B) at 960 Hz. Data was collected with the Qualisys QTM software (Qualisys AB, Gothenburg, Sweden).

Procedures

Participants reported to the lab for 2 sessions: a familiarization and a testing session. During the first session the procedures of the study were explained to the participants and informed consent was obtained. Height and weight measurements of the participants were taken for model construction. Also, during the first session the subjects were familiarized with the drop jump task.

For the second session (the data collection trials) the participants were told to report to the testing area dressed in athletic wear, which includes a short sleeve compression shirt, compression shorts, regular socks, and athletic shoes.

The participants first went through an approximately ten minute dynamic flexibility warm-up that includes 3-4 minutes of light jogging followed by 9 exercises. The subject executed the movement instructed for the first 10 meters, and then accelerated for another 10 meters, and then jogged back. The dynamic flexibility warm-up exercises were as follows: 3-4 minutes of jogging at self-selected pace; Heel-toe walk; Walking calf stretch; High knees; Walking quad stretch; Butt kicks; Walking hamstring stretch; Marching with straight knees; Open the gate; Close the gate.

When the warm-up was completed the participant would return to the testing area to be instrumented with reflective markers. First a static pose was taken with both tracking and calibration makers. Then the participant would perform practice trials until they are re-familiarized and comfortable with the drop jumps. The calibration markers were then removed and the actual data trials proceeded. The participant performed the drop jumps until five successful trials were recorded. A trial was regarded as successful when the participant performed the drop jump fulfilling five criteria: Falling off the box (not jumping or stepping off); Lands in a natural and balanced manner with one foot on each force plate and is deemed visually symmetrical; Explosively performs a maximal vertical jump; Lands again with one foot on each force plate and stabilizes visually symmetrical; During the task the subject's hand must stay stationary by their ears to not obstruct the cameras from collecting data from any of the reflective markers.

Data Processing and Reduction

C-Motion Visual 3D was used for data processing. A 4^{th} order zero-lag Butterworth filter with a cut-off at 12 Hz used to process the kinematic and kinetic data. Initial ground contact was defined as the first point where vGRF exceeded a force of 10 N. Joint moments for the hip, knee, and ankle were calculated using inverse dynamics solutions. Then joint power was calculated for each respective joint as the product of joint moment (Nm) and joint velocity (rad/s). Energy absorption was calculated by integrating the negative portion of the joint power curve from initial contact with the force platforms to peak knee flexion angle. Power production was calculated by integrating the positive portion of the joint power curve from peak knee flexion to peak vertical center of mass displacement. The energetics data was then normalized to body weight (N) and height (m) (Decker et al., 2003; Shultz et al., 2012).

Statistical Plan

The preferred and non-preferred limbs were the independent variables. Sagittal plane hip, knee, and ankle energetics for both limbs were the dependent variables. Two separate 2 x 3 Analysis of variance (ANOVAs) with repeated measures (between = limb(2); within = joints(3)) were used to compare energy absorption and power production across the two limbs. An *a priori* power analysis (G*Power 3.1) indicated that for a repeated measures ANOVA with two between and three within factors with a moderate effect size of 0.25, that 44 subjects were needed to detect an alpha level of less than 0.05 with 95% power.

RESULTS

A total of 44 (22 males, 22 females) participants (1.71 ± 0.08 m; 69.3 ± 12.1 kg; 22.3 ± 2.3 yrs) successfully completed the study. 39 of the participants reported their right leg to be the preferred kicking limb, whereas 5 participants had left leg preference.

Energy Absorption

The 2 x 3 ANOVA identified main effects for limb ($F_{1, 43} = 17.9$, $P < 0.01$) and joint ($F_{2, 86} = 15.3$, $P < 0.01$), but no limb by joint interaction ($F_{2, 86} = 0.70$, $P = 0.51$). Post hoc testing revealed that the hip absorbed more energy than the knee ($t = -4.17$, $P < 0.01$) and the ankle ($t = -7.1$, $P < 0.01$) (Figure 1).

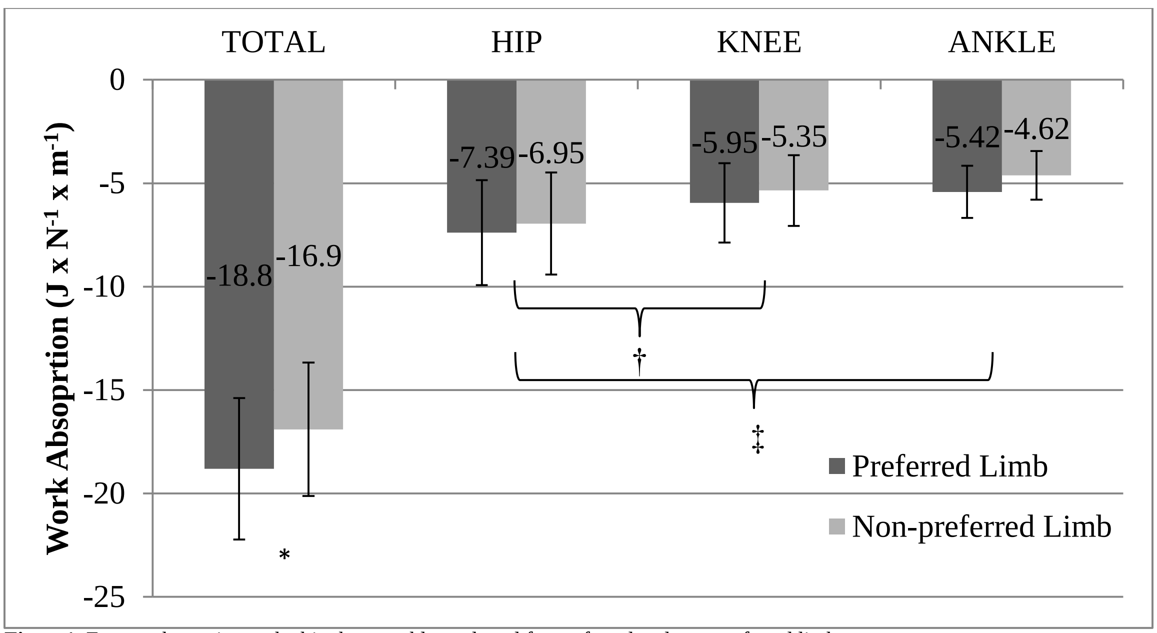

Figure1. Energy absorption at the hip, knee, ankle, and total for preferred and non-preferred limb.

Values expressed as x100

* Preferred limb > Non-preferred limb

† Hip > Knee

‡ Hip > Ankle

Power Production

For power production, main effects were identified for limb ($F_{1, 43}$ = 10.05, P <0.01) and joint ($F_{2, 86}$ = 24.0, P < 0.01). The preferred limb produced more power than the non-preferred limb (t = 3.72, P < 0.01). Post hoc testing revealed that the hip produced more power than the knee (t = 7.36, P < 0.01) and the ankle (t = 7.26, P < 0.01). There was also a limb by joint interaction ($F_{2, 86}$ = 4.96, P < 0.01). Post hoc testing showed that power production was greater in the preferred knee (t = 3.30, P < 0.01) and ankle (t = 4.84, P < 0.01), with no difference at the hip (t = -0.06, P = 0.95) (Figure 2).

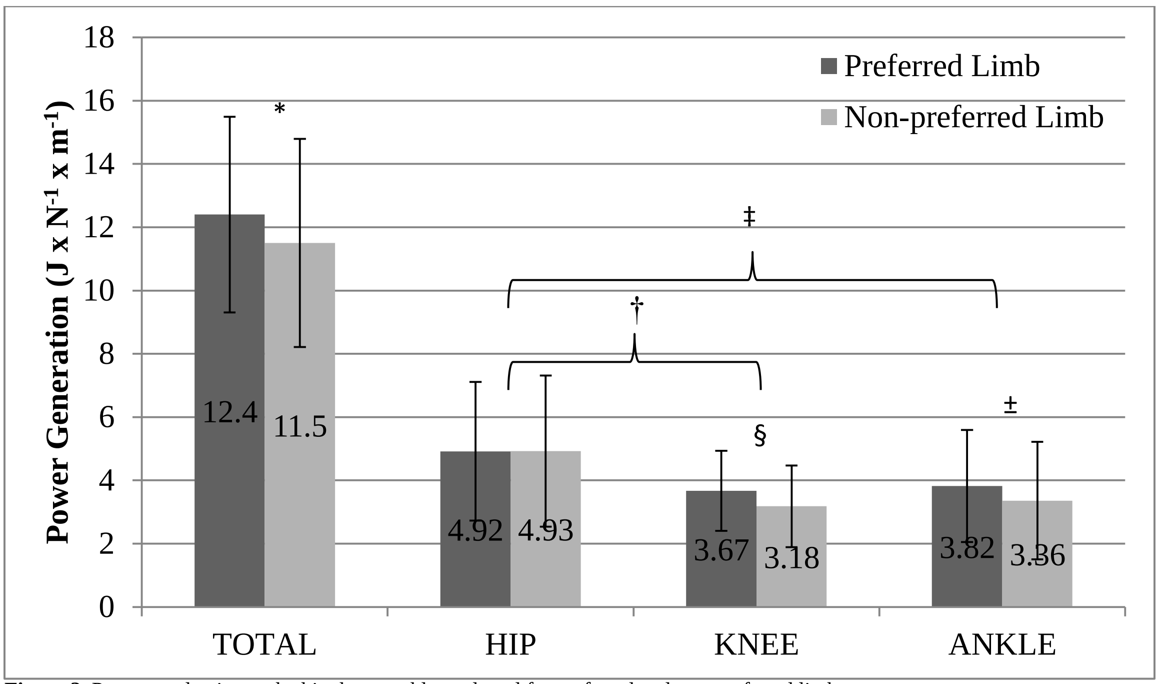

Figure 2. Power production at the hip, knee, ankle, and total for preferred and non-preferred limb.

Values expressed as x100

* Preferred limb > Non-preferred limb

† Hip > Knee

‡ Hip > Ankle

§ Preferred knee > Non-preferred knee

± Preferred ankle > Non-preferred ankle

DISCUSSION

The purpose of this study was to investigate asymmetry in lower extremity energetics during a bilateral drop jump landing task. The main findings were that the preferred limb absorbed more energy and produced more power. These findings partially supported the hypotheses of this study.

Energy Absorption

The relative joint contribution during absorption was 40% for the hip, followed by 32% for the knee, and lastly 28% for the ankle. These subjects absorbed more energy at the hip and knee, compared to the ankle, which indicates that they used a soft landing technique. During softer landings the musculature of the hip and knee absorb more energy partially due to increased range of motion, therefore, decreasing the risk for injury as less energy is absorbed by the passive structures of the lower extremities (Devita & Skelly, 1992; Zhang et al., 2000). This strategy is similar to previous work that used a drop landing task (DeVita & Skelly, 1992: Zhang et al., 2000; Decker et al., 2003). However our findings of the lower contribution seem to be inconsistent with some previous research on drop jumps. Montgomery et al. (2014) used drop jump from a height of 0.45m and reported the knee to be the main shock absorber for both males and females (56.0% vs. 60.5%), followed by the hip (22.4%) and ankle (21.6%) in males, and ankle (21.3%) and hip (18.1%) in females. The reason for differences in joint contributions between our study and this study is not clear as similar drop jump procedures have been reported, however the study recruited primarily NCAA Division I athletes and that may have been a factor as more skilled athletes were used. In addition, our findings of the lower contribution of the ankle seem to be inconsistent with previous research on drop jumps from a height of 0.45m.

Past literature on drop jumps has reported relative joint contributions of the ankle ranging from 42%-47% (Schmitz et al., 2010; Shultz et al., 2010; Shultz et al., 2012) which is much greater than the 28% reported in our study. A larger proportion of energy absorbed by the ankle is indicative of a stiffer landing technique (Zhang et al., 2000). Furthermore, in contrast to our study, the same studies reported much smaller contributions at the knee (14%-24%), but fairly similar relative contributions at the hip (33%-42%) (Schmitz et al., 2010; Shultz et al., 2010; Shultz et al., 2012). The reason for these discrepancies in relative joint contributions is not fully clear however factors that may influence landing technique may be the athletic experience of the participants and drop jump procedures. For example, previous work (Schmitz et al., 2010; Shultz et al., 2010; Shultz et al., 2012) included physically active participants but did not require jumping experience of activities which likely means that some of their participants were not skilled at jumping. Furthermore, instructions given by the researcher may affect landing strategy, as different commands were used to inform the participants on how to perform the following jump after landing. For example, if the participants are instructed to land and jump as quickly as possible, they may use more of an ankle bouncing strategy. This would result in a stiffer landing strategy because of the instructions encouraging less ground contact during initial landing and may therefore explain the increased energy absorption at the ankle.

We hypothesized that the non-preferred limb would play a larger part in deceleration and stabilization, therefore absorbing more energy; however, this was contrary to our findings. Because of the lack of literature on lower limb asymmetry during landing, we based our hypothesis on the gait literature. This body of research identified the non-preferred limb to be more heavily involved in control (deceleration and stabilization), while the preferred limb exhibited more propulsion behavior (Sadeghi et al., 1997; Sadeghi et al., 2000; Sadeghi et al., 2001). However, landings are dissimilar from gait because of the higher forces and stretch-shortening behavior. Therefore it appears that lower limb behaviors during gait may not be applied to dynamic landing tasks.

During landing, great mechanical demand is placed on the lower extremity due to the kinetic energy generated when falling from a height. The musculature of the lower extremities is responsible for dissipating the majority of that energy and to decelerate the body by the means of eccentric muscle action (Devita & Skelly, 1992; Zhang et al., 2000). Previous work has shown that maximal isometric (Schmitz & Shultz, 2010) and eccentric (Montgomery, Shultz, Schmitz, Wideman & Henson, 2012) quadriceps and hamstring strength influenced the amount of energy absorption. However, both these studies reported a stronger relationship between strength and energy absorption in females compared to males (Schmitz & Shultz, 2010; Montgomery et al., 2012). Nonetheless, it appears that more strength would lend towards a greater capability of the preferred limb to absorb energy and would help explain our findings.

Whether a greater reliance on one limb for energy absorption influences injury risk remains speculative. If there is a greater reliance on one limb to absorb landing forces, it is possible that the risk of injury may increase. While the preferred limb may be able to absorb more energy, this limb may also be more at risk for injury as it might be compensating for the non-preferred limb. In the event of an unexpected or awkward maneuver where the muscles do not absorb the energy and it is instead taken up in the passive structures, the overreliance on the preferred limb could therefore put it at more risk for injury. This theory may be supported by previous work which reported that 74.97% of non-contact ACL injuries occurred to the preferred (kicking) limb in male soccer players (Brophy et al., 2010). In contrast, it could also be argued that if there is no compensation for the less skilled limb, then the non-preferred limb may be at more risk for injury. This theory could explain the previous finding that 67.7% of non-contact ACL-injuries in females occurred to the non-kicking leg (Brophy et al., 2010).

More work is needed to understand how side-to-side differences in energy absorption behaviors may lead to an increased risk of injury but the findings of this study may provide some initial evidence.

Power Production

During the propulsion phase the hip generated the most power (41%), with the knee (29%) and ankle (30%), producing similar relative amounts of power. This is similar to previous research that looked at drop jumps from a height of 0.30m and reported relative joint contributions of the hip, knee, and ankle of 38%, 34%, and 28% respectively (Moran & Wallace, 2007). In contrast, another study looking at drop jumps from a height of 0.40 m reported the knee to generate the most power (37%), followed by the hip (33%), and ankle (29%) (Bobbert, Mackay, Schinkelshoek, Huijing & Ingen

Schenau, 1986). The same pattern where the hip or the knee is reported to generate the most power is seen in other literature on both drop jumps and countermovement jumps (Hubley & Wells, 1983; Vanezis, & Lees, 2005; Moran & Wallace, 2007). The reason for these small discrepancies are not fully clear, however it may be due to subject population as they range from healthy male college students to elite handball, and volleyball players. As mentioned earlier, sport-specific training and goals (i.e. jumping for maximum height vs. quick change of direction) may result in different adaptations in the lower extremities and therefore explain the differences in relative joint contributions in power generation across studies. It should also be noted that the literature mentioned only used male subjects whereas our study included equal number of males and females. This may affect the results as females have been shown to differ from males during vertical countermovement jumps in several kinetic and kinematic parameters, such as vGRF, joint angles, and joint moments (Stephens, Lawson, DeVoe, & Reiser, 2007).

Our data supported our hypothesis that the preferred leg would exhibit greater power generation during the propulsion phase of the drop jump. There was no side-to-side difference in power generation at the hip; however both the knee and the ankle in the preferred limb generated more power.

The reason that the preferred limb generated more power is not fully understood, however it may be attributed to factors not assessed in this study such as lean mass and strength asymmetries. Previous work has shown lean mass asymmetries of greater than 10% in about 50% of their subjects who represented a range of sports (Bell, Sanfilippo, Binkley, Heiderscheit, 2014). Strength asymmetries have also been shown in professional soccer players ranging from 6.7%-14.3% in the knee and 8.2%-10.2% in the ankle

(Fousekis et al., 2010) Since lean mass in the lower extremity is a determinant to the amount of peak eccentric torque that one can produce (Montgomery et al. 2012) and strength is a major determinant to power output (Stowers, Mcmillan, Scala, Davis, Wilson & Stone, 1983; Wilson, Newton, Murphy & Humphries, 1993), it appears that asymmetries in lean mass and/or strength could affect power production. In support of this premise, a recent study showed that lower extremity lean mass asymmetry explained 25% of variance in power asymmetry and further, that possessing more than 10% power asymmetry tended to decrease vertical jump performance (Bell et al., 2014). However, these findings are in contrast to a computer simulation study which showed that a bilateral strength asymmetry of 10% did not have a significant effect on vertical jumping performance. The authors concluded that the stronger leg compensated for the weaker leg by a lateral shift in body weight proportional to the strength differences (Yoshioka, Nagano, Hay & Fukashiro, 2010). It appears that more work is needed to determine the impact of asymmetry in lean mass and strength asymmetries on asymmetry in power production.

Another factor to consider is enhanced neuromuscular control as it has been shown to increase maximal muscle activation and rate of muscle activation. Both these factors have been linked to greater power production (Cormie, Mcguigan & Newton, 2010) and may be of importance when looking at asymmetries as sport specific training has been shown to lead to asymmetries (Luk, Winter, O'Neill & Thompson, 2014) and different neuromuscular adaptations (Cormie et al., 2010). For example it has been shown that a population exposed to a 10 week ballistic power training program saw increases in power production due to increased rate of EMG rise and enhanced stretch-shortening function, whereas a 10 week heavy strength training program resulted in greater power production due to increased maximal neural activation and muscle thickness (Cormie et al., 2010). Combining the conclusions of this study with a past study on force asymmetries in field jumpers (unilateral jumpers) versus powerlifters (bilateral jumpers) where more asymmetry was seen in the field jumpers (Luk et al., 2014), one may draw the conclusion that sport specific training may lead to neuromuscular asymmetries between the limbs. Furthermore, timing of muscle activation has also been shown to affect power output, for example, it has been reported that early activation of the biceps femoris may compromise power performance (Pereira, Machado, dos Santos, Pereira & Sampaio-Jorge, 2008).

Our data revealed greater power production from the preferred limb during a maximal vertical jump. It appears that the underlying reasons may include a combination of lean mass, strength and neuromuscular control. Since all of these elements that can be enhanced through training and sport-specific skill training, future work should investigate the extent to which addressing each component can improve symmetry in power production.

CONCLUSION

During a drop jump landing, the preferred limb absorbed more energy during the deceleration phase of landing and also generated more power during propulsion for a maximal vertical jump. It appears that the asymmetries may be due to underlying functional asymmetries such as strength and neuromuscular control. The findings in this study indicate asymmetrical performance of the lower limbs, and specifically that there may be a greater reliance on the preferred limb for both deceleration and propulsion behaviors. It is possible that the greater energetics and power production demands on the preferred limb could place the limbs at greater risk of injury. If this is the case, then it may have important implications for specific training and rehabilitation; specifically, that asymmetries in structure and function need to be addressed. For example, because males have been shown to suffer ACL injury in the preferred limb more frequently than the non-preferred limb (Brophy et al., 2010), it may be necessary for male athletes to place an emphasis on training the preferred limb to correct asymmetries.

Limitations and Future Study

A limitation of our study was that we only investigated sagittal plane mechanics. Frontal and transverse plane mechanics during gait have been linked to balance and support during dual-limb tasks (Sadeghi et al., 1997; Sadeghi, et. al 2000; Sadeghi et al., 2001); however whether that applies to a dynamic landing task (where injury typically occurs) is unknown. Separating subjects by sex could also be a part of future research since it has been reported that males and females have different energy absorption strategies during drop jumps (Decker et al., 2003; Schmitz et al., 2010) and also that the relationship between strength and energy absorption appears to differ between males and females (Shultz et al., 2010; Montgomery et al., 2012). Together, this work could help explain the sex differences in injury patterns whereby males tend to injure their preferred limb more often while females injure the non-preferred limb (Brophy et al., 2010).

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APPENDIX A

Effect Sizes

A-1. Normalized Energy Absorption (EA) and Power Production (PP) values (J^{-1} x N^{-1} x m^{-1}). Mean±SD and range (min-max) and between-limb effect sizes are provided.

	Preferred Limb	**Non-preferred Limb**	**t**	**P-value**	**Effect Size d**
Hip EA	7.39±2.53 (2.07-13.4)	6.95±2.47 (1.90-13.0)	1.60	0.12	0.24
Knee EA	5.95±1.92 (1.76-9.93)	5.35.±1.71 (1.00-8.15)	2.94	<0.01†	0.44
Ankle EA	5.42±1.26 (3.67-9.68)	4.62±1.17 (2.56-7.27)	4.07	<0.01†	0.62
Hip PP	4.92±2.19 (1.06-9.85)	4.93±2.39 (1.05-9.06)	-0.06	0.95	0.01
Knee PP	3.67±1.27 (1.35-6.77)	3.18±1.29 (0.56-6.28)	3.30	<0.01†	0.50
Ankle PP	3.82±1.77 (1.13-7.44)	3.36±1.86 (0.88-6.97)	4.84	<0.01†	0.73

* Values are displayed x10^2
† Indicates Preferred > Non-preferred ($p<0.05$)