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A Kinematic Analysis of Techniques Used by Elite Transtibial and Transfemoral
Amputee Long Jump Athletes

(Under the direction of KATHY J. SIMPSON)

Limited biomechanical research exists regarding optimal performance techniques of transtibial (TranTib) and transfemoral (TranFem) amputee long jump athletes. As such, the purpose of this study of elite TranTib and TranFem athletes was to determine how the kinematic characteristics exhibited during long jump performances varied between higher and lower skilled long jump athletes.

All of the long jump performances of the women's long jump (four TranTib and one TranFem) and the men's long jump and pentathlon competitions (six TranTib and four TranFem) were videotaped for analysis at the 1998 Ultimate Challenge Track and Field Invitational and 1999 National Summer Games, respectively. The farthest legal jump for each participant was selected for analysis. Due to the small sample sizes, non-parametric statistics (Kolmogorov-Smirnov, Mann-Whitney U, and chi-square tests) were used to analyze hypotheses related to selected techniques and skill level ($p < 0.05$).

For the TranTib athletes, only two comparisons were statistically significant. However, these findings were influenced by gender. The men dropped while the women raised the body's COM (COM_B) during the penultimate stride of the approach. Thus, it is not known if dropping the COM_B is advantageous for the TranTib athletes. Although the top two TranFem athletes did not always exhibit optimal performance techniques, in general, the following performance techniques were used by the higher skilled TranTib and TranFem athletes:

1. Approach technique (TranTib and some TranFem men): COM_B was lowered during the penultimate stride of the approach and then lowered further until touchdown onto the takeoff board.
2. Active landing technique onto the takeoff board: placed the takeoff foot onto the takeoff board in a backward sweeping motion.

3. Flight technique: higher skilled athletes performed the flight technique appropriate to their flight time.
4. Body position prior to landing: in general, a small lower leg landing angle was achieved by the athletes extending the knee joints and flexing the trunk about the lower vertebral joints (action) causing a reaction of hip flexion.

INDEX WORDS: Biomechanics, Lower extremity amputee, Sport, Track and field

A KINEMATIC ANALYSIS OF TECHNIQUES USED
BY ELITE TRANSTIBIAL AND TRANSFEMORAL
AMPUTEE LONG JUMP ATHLETES

by

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CHAPTER I

INTRODUCTION

Background

In 1896, Athens, Greece was the site for the first modern Olympic Games. It was during these Olympic Games that the running long jump made its debut as a track and field Olympic event (Encyclopedia of Track and Field, 1986). However, competition is reserved for athletes without physical limitations. Therefore, the Paralympic Games were developed to accommodate athletes with functional disabilities that prevent them from competing in the Olympic Games. The first Paralympic Games were held in Rome, Italy, in 1960 (<http://www.paralympic.org>). Athletes that have visual impairments, cerebral palsy, spinal cord injuries, dwarfism, or limb amputations compete in the Paralympic Games (<http://www.olympic-usa.org>).

Since the first Olympic and Paralympic Games, the long jump has become a highly competitive track and field event where the margin of victory for a gold medal can be as little as 0.01 m. Numerous biomechanical studies have been conducted to determine optimal performance techniques that long jump athletes without physical limitations may use to produce a maximal length jump (for review, see Hay, 1986; Hay, 1993a). However, for athletes with physical limitations, specifically lower extremity amputations, the biomechanical research available regarding optimal long jump performance techniques and the underlying biomechanics is limited (Nolan & Lees, 1999; Simpson, Williams, Ciapponi, Wen, Nance, & Valleala, 1998; Williams, Simpson, & Del Rey, 1997).

Performance techniques differ between athletes with versus without a lower extremity amputation due to two factors: loss of musculoskeletal tissues (Martin & Sanderson, 1998) and the use of a prosthetic component. The prosthetic component must

substitute for the functions of the tissues that were removed or compromised during the amputation procedure. As such, during locomotor movements, the prosthetic component is responsible for absorbing impact forces and storing energy during impact with the ground and releasing stored energy during the propulsive phase to partially compensate, but not completely replace muscle force, joint stability, and limb positioning (Brouwer, Allard, & Labelle, 1989; Ehara, Beppu, Nomura, Kunimi, & Takahashi, 1993).

Thus, from the findings of the running literature, it has been demonstrated that lower extremity amputee participants modify their running gait technique compared to non-amputee (NonAmp) participants to compensate for the limitations associated with the prosthetic limb (ProsL) and prosthesis (Brouwer et al., 1989; Enoka, Miller, & Burgess, 1982). Therefore, consistent with the amputee running literature (Brouwer et al., 1989; Enoka et al., 1982), for the long jump approach (Simpson et al., 1998; Williams et al., 1997), asymmetrical running gait patterns are exhibited by transtibial (TranTib) and transfemoral (TranFem) amputee individuals. Reduced stride length, stride time, and ankle range of motion are produced by the ProsL compared to the non-prosthetic limb (NProsL) (Brouwer et al., 1989; Enoka et al., 1982; Simpson et al., 1998; Williams et al., 1997).

For the long jump, during the takeoff phase, elite TranTib and TranFem athletes have demonstrated other techniques that also appear to occur as adaptations to the unique constraints of the ProsL and prosthesis (Nolan & Lees, 1999; Simpson et al., 1998; Williams et al., 1997). For example, Nolan and Lees observed that the TranFem athletes had a higher body's center of mass (COM_B) height at touchdown onto the takeoff board than the TranTib and NonAmp athletes. This phenomenon was surmised to be a consequence of the lack of a fully functional knee that prevented the athletes from being able to flex the knee (Nolan & Lees, 1999). Nolan and Lees also found that both TranTib and TranFem athletes had greater hip flexion than NonAmp athletes at touchdown onto the takeoff board, thereby also increasing the hip joint range of motion during the takeoff phase. They suggested that this action reflected the use of the hip joint rather than the

knee joint as the pivot point to rotate the COM_B in order to convert horizontal velocity to vertical velocity at takeoff (Nolan & Lees, 1999).

However, the existing long jump biomechanical research for lower extremity amputee athletes is limited (Nolan & Lees, 1999; Simpson et al., 1998; Williams et al., 1997). Consequently, not much is known about the mechanics of the long jump as performed by lower extremity amputee long jump athletes. First, the mechanics underlying the modified techniques used by the TranTib and TranFem athletes are not well understood. Second, the TranTib and TranFem long jump literature reflects a narrow focus. Although the mechanics of each phase of the long jump (approach, takeoff, flight, and landing) play an integral role in producing a maximal length jump, the only phases of the long jump that have been studied for TranTib and TranFem athletes are the approach (Simpson et al., 1998; Williams et al., 1997) and takeoff phases (Nolan & Lees, 1999). The flight and landing phases have been ignored in published research.

As explained in detail in the ‘Premises of the Study’ section (see pp. 4), in this study, a more comprehensive understanding of the kinematics of the entire jump was sought. As such, the intent of this study was focused on determining how TranTib and TranFem athletes (a) transition from running at near maximal horizontal velocity (approach phase) to generating vertical velocity at takeoff (takeoff phase), (b) perform an appropriate flight technique associated to the time spent in the air (flight phase) and (c) land in such a way as to maximize the horizontal distance of the jump (landing phase).

Purpose of the Study

The purpose of this study of elite TranTib and TranFem athletes was to determine how the kinematic characteristics exhibited during long jump performances varied between higher (longer jump distance) and lower skilled long jump athletes.

Significance of the Study

Whether TranTib and TranFem athletes should use the same movement techniques as elite NonAmp athletes to make similar use of mechanical principles during locomotor activities is controversial. It is likely that for running, overall interlimb

symmetry, e.g., similar stride lengths, is maintained by more highly skilled TranTib athletes, but at the body segment level, differences between the ProsL and NProsL exist. These differences exist because compensatory actions occur in response to the use of a prosthesis that has different mechanical properties than an intact limb, e.g., force generating properties and inertial characteristics; and due to the changes in the residual limb, e.g., loss of musculature and neuromuscular control (Brouwer et al., 1989; Ehara et al., 1993; Sanderson & Martin, 1996). Therefore, during various phases of the long jump, the constraints related to the prosthesis and residual limb also may influence the mechanics exhibited by the long jump athletes. Thus, the long jump is an ideal movement for investigating how TranTib and TranFem athletes adapt to the morphological and environmental constraints related to the residual limb and prosthesis, respectively.

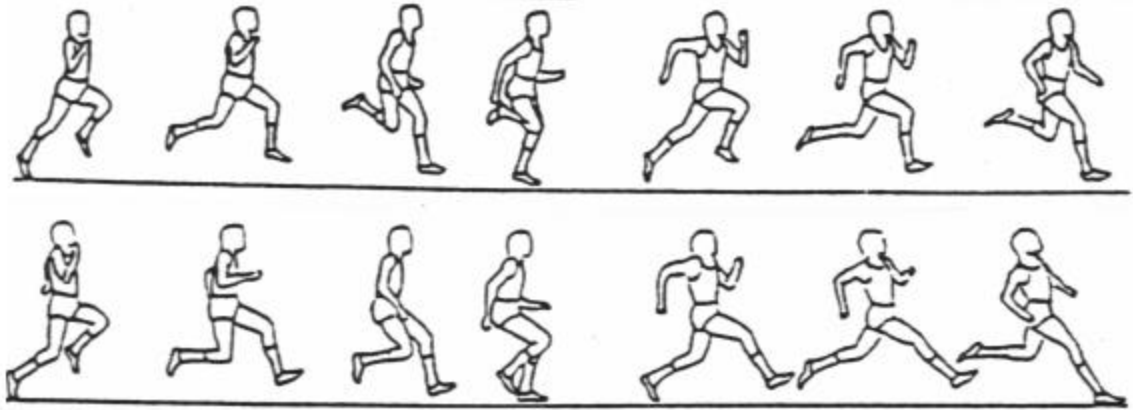
As training resources and competitions for NonAmp athletes and lower extremity amputee athletes continue to merge, a variety of people, e.g., coaches and prosthetists, need to know what performance techniques may be uniquely optimal for TranTib and TranFem long jump athletes. In summary, the results of this study provide a better understanding of the underlying biomechanical principles of long jump performance techniques specific to long jump athletes with lower extremity amputations, allowing these athletes to have scientific evidence to guide their improvements in performance.

Premises of the Study

In this section, the underlying premises and hypotheses of the study are explained in order of the four phases of the long jump: approach, takeoff, flight, and landing.

Approach Phase

The approach phase is a continuous running movement starting with the first movement of the athlete on the runway and ending when the takeoff foot is planted on the takeoff board (see Figure 1a). The mechanical purpose of the approach phase is to generate as much horizontal velocity as possible that is controllable at takeoff and to



(a) Approach phase



(b) Takeoff phase

(c) Flight phase



(d) Landing phase

Figure 1. The four phases of the long jump: (a) approach, (b) takeoff, (c) flight, and (d) landing. Taken from Tidow (1990).

place the takeoff foot onto the takeoff board as close as possible to the front edge of the takeoff board without stepping over it. The approach phase can be broken down into an initial and a final sub-phase. The initial sub-phase, the first 14-20 strides¹ of the approach, is used to generate horizontal velocity (Hay, 1993c). The initial sub-phase of the approach is the one part of the long jump that is outside the realm of this study. The final phase, the last three to four strides of the approach, is used to position the body in preparation for the takeoff phase and to contact the takeoff board accurately (Hay, 1993c).

In preparation for takeoff, during the final sub-phase of the approach, long jump athletes perform either the 'traditional' or the 'gather' approach technique (see Figure 2). The traditional technique is an approach technique in which the downward vertical displacement of the COM_B during the penultimate (next-to-last stride) stride is not deliberately modified during the approach. For NonAmp athletes, this approach technique minimizes the loss of horizontal velocity throughout the last two strides, but there is less of an increase in vertical takeoff velocity compared to that generated during the gather technique (Ciapponi, 1996).

In contrast to the traditional technique, the gather technique promotes a greater increase in vertical takeoff velocity but more of a decrease in horizontal takeoff velocity (Koh & Hay, 1990). During the gather approach technique, the athlete deliberately drops the COM_B an average of 0.03 – 0.05 m during the penultimate stride of the approach phase (see Figure 2) (Hay, 1993a; Hay & Nohara, 1990; Koh & Hay, 1990; Lees, Fowler, & Derby, 1993; Luhtanen & Komi, 1979; Tidow, 1990; Weidner & Dickwach, 1990). According to Tidow (1990), the athlete drops the COM_B during the penultimate stride by not completely extending off the back support leg. Additionally, Hay (1993a) and Lees, Graham-Smith, and Fowler (1994) state that the athlete drops the COM_B by placing the

¹ A running stride is defined as from touchdown of one foot to touchdown of the other foot. A running cycle is composed to two running strides or from touchdown of a given foot until the next touchdown of the same foot (Hay, 1993b).

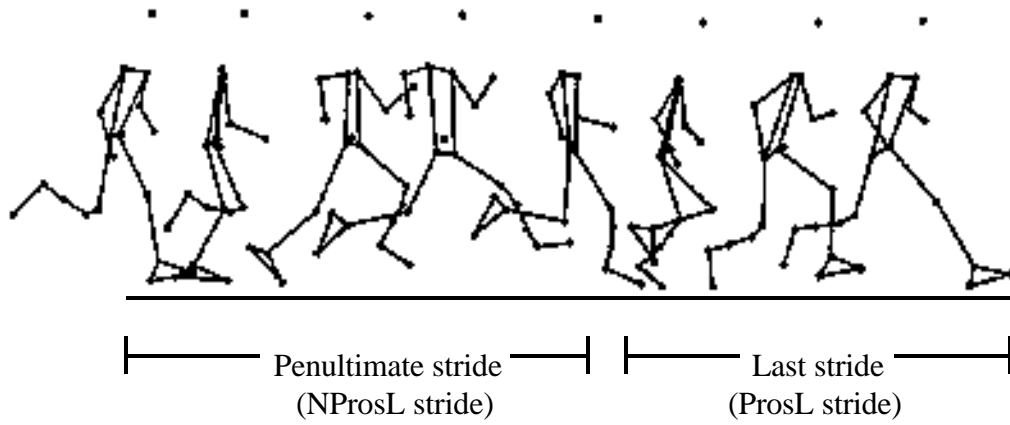


Figure 2. The penultimate stride and last stride of the gather approach technique. The triangular-shaped foot is the non-prosthetic (NProSL) foot.

touchdown foot farther in front of the COM_B which also results in a longer penultimate stride than the previous and last approach strides

For TranTib and TranFem long jump athletes, it was not clear what approach technique would typically be used. Whether the higher skilled athletes for this study would exhibit a lowered COM_B during the penultimate and/or last stride of the approach may be influenced by the mechanics of the ProsL. First, although not documented, the length and design of the prosthesis is such that the length of the ProsL is longer than the NProsL (unpublished observations). If this is true, then maintaining a lower COM_B during the last stride becomes even more difficult. In addition, the differential in limb lengths could possibly influence stride lengths.

Second, during the gather approach technique, the COM_B must remain low during the last stride until contact onto the takeoff board. Nearly all amputee long jump athletes start the penultimate stride by propelling the body from the NProsL and ending the stride by landing onto the ProsL. For some participants, maintaining a low COM_B during the last stride may not occur. This is based on observations that during the support phase of running, the ProsL demonstrates less knee extensor moments (Brouwer et al., 1989; Miller, 1987), less knee flexion during all phases (Enoka et al., 1982; Gavron & Dawson, 1995; Sanderson & Martin, 1996), and less maximum hip extension at takeoff (Brouwer et al., 1989; Miller, 1987) compared to the NProsL. Furthermore, in contrast to the NonAmp long jump athletes, the TranTib and TranFem athletes continued to lower the COM_B during the initial takeoff phase (Nolan & Lees, 1999). Nolan and Lees surmised that consequently, the TranTib and TranFem athletes had less time to develop upward vertical momentum than the NonAmp athletes. Therefore, it appears that the COM_B of the TranTib and TranFem athletes was not sufficiently lowered prior to touchdown onto the takeoff board.

The amount of lower extremity flexion during the support phase affects the vertical displacement of the COM_B (Sanderson & Martin, 1996). Several studies have reported that TranTib (Enoka et al., 1982; Gavron & Dawson, 1995; Sanderson & Martin,

1996) and TranFem (Ciapponi, Simpson, Wang, McKee, & McAllister, 1999; Wang, Simpson, Ciapponi, McKee & McAllister, 1999) athletes had less ProsL than NProsL knee flexion during the running support phase. Thus, some athletes may not drop the COM_B due to the potential difficulty of maintaining a flexed knee during the last stride of the approach, in which the ProsL is the support limb.

Third, other kinetic and kinematic interlimb differences, e.g., propulsive impulse, create interlimb asymmetry for some TranTib and TranFem long jump athletes during running that result in longer stride lengths for the NProsL compared to the ProsL which may influence the athletes ability to lower the COM_B (Buckley, 1999; Ciapponi et al., 1999; Enoka et al., 1982; Gavron & Dawson, 1995; Miller, 1981; Sanderson & Martin, 1996; Simpson et al., 1998; Wang et al., 1999). Thus, whether an athlete of this study would lower the COM_B by increasing the penultimate stride length, may be dependent upon the degree of interlimb stride length symmetry/asymmetry, particularly for TranFem athletes (Buckley, 1999; Ciapponi et al., 1999; Enoka et al., 1982; Gavron & Dawson, 1995; Miller, 1981; Sanderson & Martin, 1996; Simpson et al., 1998; Wang et al., 1999). If the NProsL stride length is greater than ProsL stride length, the penultimate stride should be longer than the previous and last stride of the approach. Therefore, the penultimate stride length also had to be longer than the previous NProsL stride (fourth-to-last stride). It was expected that the higher skilled TranTib and TranFem long jump athletes would have a longer penultimate stride length than the previous stride, as well as the previous NProsL stride (fourth-to-last stride), and last stride of the approach.

In an unpublished technical report, Simpson, Williams, Ciapponi, Wen, and Nance (1997) reported that five out of ten TranTib athletes at the 1996 Paralympic Games exhibited a longer penultimate stride length than the previous stride, perhaps suggesting that the COM_B was lowered. In addition, Nolan and Lees (1999) reported that elite male TranFem athletes had a higher COM_B height compared to TranTib and NonAmp long jump athletes while TranTib compared to NonAmp long jump athletes, had similar COM_B height at touchdown onto the takeoff board. This suggests that the

COM_B for the TranTib athletes had been lowered prior to touchdown onto the takeoff board. However, this finding may have been influenced by the height of the athletes or interparticipant variability.

As such, it was expected that for this study the higher skilled athletes would exhibit a gather approach technique, i.e., they would demonstrate a negative vertical displacement of the COM_B a minimum of 0.03 m or more (Hay & Nohara, 1990) during the penultimate stride of the approach. It was also expected that the athletes that performed a gather approach technique would have a greater decrease in horizontal velocity and a greater increase in vertical velocity from touchdown onto the takeoff board until the instant of takeoff than the athletes who performed the traditional approach technique.

Takeoff Phase

The takeoff phase is a discrete movement that begins with the plant of the takeoff foot onto the takeoff board and ends the instant the takeoff foot leaves the takeoff board (see Figure 1b). The mechanical purpose of the takeoff phase is to: (a) obtain vertical velocity while maintaining as much horizontal velocity as possible, (b) optimize the body's COM height at takeoff and (c) project the body into the air at an optimal takeoff angle of less than 45° (Hamill & Knutzen, 1995).

During the takeoff phase, there is a tradeoff between maintaining the magnitude of horizontal velocity and generating vertical velocity; as one increases, the other decreases. This is due to technique constraints as well as the mathematical relationship between the resultant ground reaction forces and the anteroposterior and vertical components generated during the takeoff phase (Nelson & Zebas, 1990; Young & Marino, 1984). Young and Marino (1984) found that for NonAmp long jump athletes, horizontal velocity at takeoff was more influential on the distance jumped than vertical velocity at takeoff. As a result, the vertical velocity of the COM_B generated at takeoff is less than mechanically optimal because the athlete wants to minimize the loss of horizontal velocity during the takeoff phase.

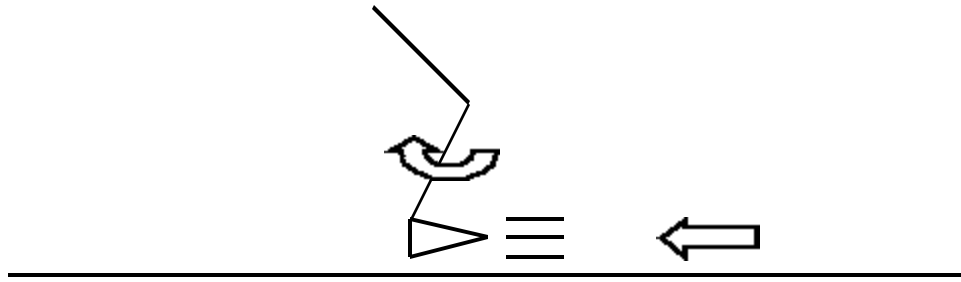
To either maintain horizontal velocity or augment the generation of vertical velocity at takeoff, two methods of placing the support leg onto the takeoff board (or the ground) have been used, the ‘active landing’ and ‘height’ techniques (see Figure 3a-b, respectively). The active landing technique is performed by the athlete pulling the touchdown foot backwards using a pawing action. This action places the touchdown foot slightly in front of the COM_B at a velocity close to 0 m/s relative to the ground (Koh & Hay, 1990). Subsequently, during the takeoff phase, the COM_B quickly passes over the takeoff foot, thereby also minimizing the amount of time in which vertical momentum can be generated for takeoff (Marino & Young, 1990; McLean, 1995). However, the braking impulse is also minimized.

In contrast, the height technique is performed by the athlete bringing the touchdown foot down in front of the body’s COM in a blocking manner. By placing the takeoff foot in front of the horizontal position of the body’s COM, the athlete spends more time on the takeoff board, allowing for a greater generation of vertical velocity for takeoff than with the active landing technique (Marino & Young, 1990; McLean, 1995). However, more importantly, the active landing technique compared to the height technique maintains more horizontal velocity at takeoff (Bosco, Luhtanen, & Komi, 1975; Hay & Miller, 1985; Koh & Hay, 1991; Marino & Young, 1990).

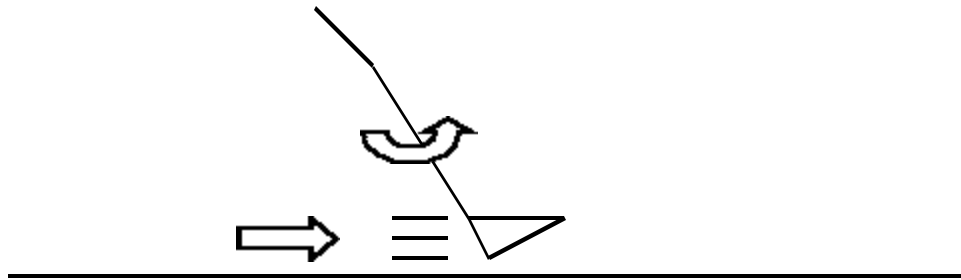
The landing technique that the TranTib and TranFem long jump athletes of this study would perform was unknown. However, it was expected that the higher skilled TranTib and TranFem athletes would perform an active landing technique for two reasons: (a) to take advantage of maintaining horizontal velocity and (b) because the NProsL is the limb that would perform the action of the active landing technique.

Flight Phase

The flight phase is a discrete movement that starts the instant the takeoff foot leaves the takeoff board and ends the instant the feet touch the sand (see Figure 1c). The mechanical purpose of the flight phase is to travel horizontally in the air as far as possible before contacting the sand and to control the body positioning so that during the landing



(a) Active landing technique



(b) Height landing technique

Figure 3. The (a) active landing and (b) height landing techniques.

phase, no part of the body contacts the sand behind the initial contact point (i.e., behind the landing point of the foot closest to the takeoff board).

To position the body into the optimal landing position during this phase, the athletes use one of three flight techniques: sail, hang, or hitch-kick (see Figure 4a-c, respectively). The flight technique performed may be based on two factors, the amount of angular momentum that exists at takeoff (Herzog, 1986; Tidow, 1990) and the flight time (El Khadem & Huyck, 1966). The flight time determines if the athlete has enough time to complete the rotations of the body's extremities to position the body for an optimal landing. The hitch-kick flight technique takes longer to perform than the hang or sail flight techniques so the athlete must be in the air long enough to perform the hitch-kick flight technique.

Elite NonAmp athletes tend to use the hitch-kick flight technique (Hay, 1986; Weidner & Dickwach, 1990) while all flight techniques and the sail flight technique were exhibited during the 1996 Paralympic TranTib and TranFem long jump competitions, respectively (Simpson et al., 1997). It was not known if TranTib and TranFem athletes of this study would perform a particular flight technique due to the flight time. However, it was expected that the hitch-kick flight technique would be performed by the higher skilled athletes that spent more time in the air than the lesser skilled athletes that performed the hang or sail flight techniques.

Landing Phase

The landing phase is a discrete movement that begins the instant the feet touch the sand and ends when movement ceases (see Figure 1d). The mechanical purpose of the landing phase is to safely stop movement of the body, land as far from the takeoff board as possible without subtracting from the distance of the jump by reaching or falling backwards.

Simpson et al. (1997) reported that the TranTib and TranFem long jump athletes tended to fall laterally to one side or the other upon landing. Seven out of 12 TranTib and all of the TranFem athletes fell toward the side opposite their ProsL. They postulated that



(a) Sail flight technique



(b) Hang flight technique



(c) Hitch-kick flight technique

Figure 4. The three flight techniques: (a) sail, (b) hang, and (c) hitch-kick. Taken from Adrian and Cooper (1995).

the athletes were attempting to reduce the impact forces to the residual limb. They also surmised that because the ProsL length is longer compared to the NProsL, the ProsL would contact the ground first, creating a torque in the frontal plane that would cause the body to rotate laterally, i.e., to fall toward the NProsL side. Simpson et al. also reported that four of the 22 TranTib athletes appeared to fall forward over their feet instead of using the technique of flexing the lower extremities to cause the body to move towards the feet at contact with the ground. It was surmised that this could have been due to an inability to flex the ProsL or to maintain sufficient stability of the residual limb within the socket. However, it is also possible that those athletes fell forward due to improper technique that occurred prior to landing. Based on the findings of Simpson et al., it was expected that some of the TranTib and TranFem long jump athletes would not be in an optimal landing position causing them to fall to one side or the other or to fall forward over their feet upon landing.

As previously stated, little is known about how the techniques of each phase of the long jump influence performance of TranTib and TranFem amputee athletes. The desire for athletes and coaches to have more information about techniques specific to TranTib and TranFem amputee long jump brought about the development of the following research questions and hypotheses.

Research Questions and Hypotheses

The research questions and their corresponding hypotheses for the study are as follows:

1. Will the athletes that jumped the farthest, within their amputee classification, perform a gather approach technique, drop the COM_B during the penultimate stride of the approach, by performing a penultimate stride length longer than the third-to-last and last stride lengths during the final phase of the approach?

Hypothesis 1: *The athletes that exhibit a gather approach technique, by dropping the COM_B 0.03 m or more during the penultimate stride, will demonstrate a stride length longer for the penultimate stride than the third-to-last and last strides of the approach.*

2. Will the athletes that jumped the farthest, within their amputee classification, that performed a gather approach technique: (a) have a greater decrease in horizontal takeoff velocity and a greater increase in vertical takeoff velocity from touchdown onto the takeoff board until takeoff and (b) jump farther than the athletes that performed a traditional approach technique?

Hypothesis 2:

- a. *The TranTib and TranFem athletes that performed a gather approach technique will have a greater decrease in horizontal takeoff velocity and a greater increase in vertical takeoff velocity from touchdown onto the takeoff board until takeoff than the athletes that performed a traditional approach technique.*
 - b. *The TranTib and TranFem athletes that performed a gather approach technique will jump farther than the athletes that performed a traditional approach technique.*
3. Will the athletes that jumped the farthest, within their amputee classification, perform an active landing technique by producing a negative horizontal velocity of the takeoff foot relative to the COM_B just prior to touchdown onto the takeoff board?

Hypothesis 3:

- The athletes that jumped the farthest, within their amputee classification, will create an active landing technique by producing a negative horizontal velocity of the takeoff foot relative to the COM_B just prior to touchdown onto the takeoff board.*
4. Will the TranTib and TranFem long jump athletes that performed an active landing technique compared to the height technique (a positive horizontal velocity of the takeoff foot relative to the COM_B just prior to touchdown onto the takeoff board): (a) spend less time on the takeoff board, (b) have a greater increase in

horizontal takeoff velocity and a greater decrease in vertical takeoff velocity and
(c) jump farther?

Hypothesis 4:

- a. *The TranTib and TranFem athletes that performed an active landing technique will be on the takeoff board for a shorter duration of time than the athletes that performed a height technique.*
 - b. *The TranTib and TranFem athletes that performed an active landing technique will generate more horizontal velocity and less vertical velocity during takeoff than the athletes that performed a height technique.*
 - c. *The TranTib and TranFem athletes that performed an active landing technique will jump farther than the athletes that performed a height technique.*
5. Will TranTib and TranFem long jump athletes perform a flight technique (sail, hang, or hitch-kick) congruent with their flight time?

Hypothesis 5:

The rank order (sail, hang, and hitch-kick) of the flight techniques performed by the TranTib and TranFem amputee long jump athletes will be directly related to the flight time.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this study of elite TranTib and TranFem athletes was to determine how the kinematic characteristics exhibited during long jump performances varied between higher (longer jump distance) and lower skilled long jump athletes. Lower extremity amputee literature is discussed first followed by long jump literature. The long jump literature of NonAmp and TranTib and TranFem long jump athletes is reviewed in order of the four phases of the long jump: approach, takeoff, flight, and landing.

Lower Extremity Amputee Literature

Prosthesis Design

A prosthetic device for a person with a lower extremity amputation needs to be comfortable and functional or it will not be worn (May, 1996). If the prosthesis is not worn, prosthetic rehabilitation cannot be successful. When an amputee participates in activities that require the use of a prosthesis, the prosthesis is deemed functional (May, 1996).

In order for the prosthesis to be comfortable and functional, it needs to be the optimal prosthesis available for the person. The person's physical and emotional attributes, such as health, weight, level of activity, motivation, and activity goals, influence the design of the prosthesis (May, 1996). Another factor influencing prosthetic design is the length, shape, skin condition, circulation and range of motion of the residual limb (May, 1996).

The lower extremity prosthesis is composed of a socket, knee joint (TranFem), pylon, and foot components (see Figure 5a-b, respectively). Due to the advances in

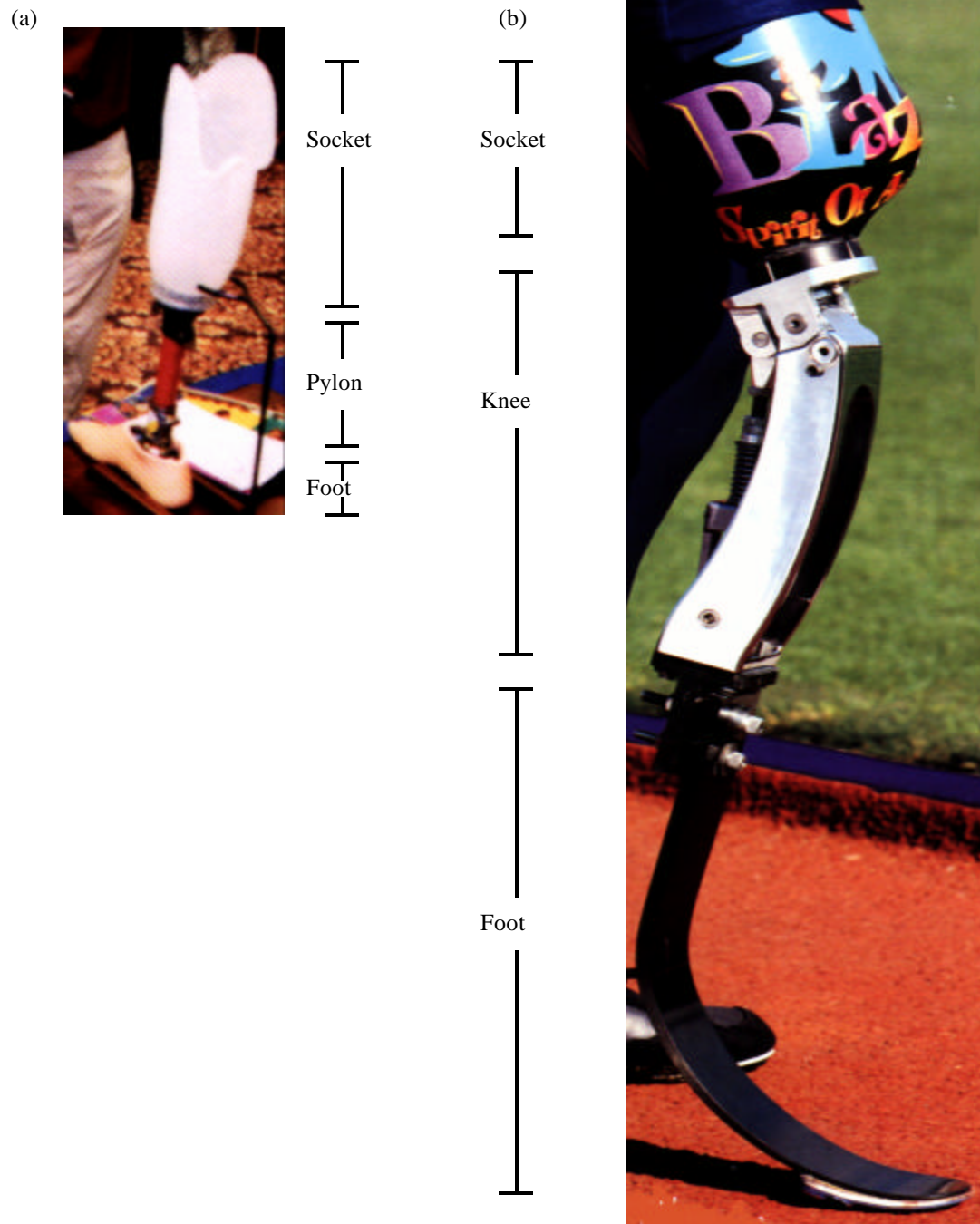


Figure 5. Parts of the (a) transtibial prosthesis and (b) transfemoral prosthesis. From inMotion (1999) and ProSport™ advertisement, respectively.

technology and material development for each of these components, there are a variety of models suitable for different purposes, e.g., walking versus sprinting.

The socket must support the amputee's body weight and hold the residual limb firmly and comfortably during any movement, from simply standing to running or jumping (May, 1996). In a popular magazine, inMotion, Carroll and Sabolich (1999) refer to the socket as the most important component because it is in contact with the amputee's body via the residual limb. As such, it is critical to obtain the best fit possible between the socket and the residual limb. This is done by a relatively new method known as 'contouring' (Carroll & Sabolich, 1999). Contouring allows the prosthetist to map the muscles, bony prominences, and vascular structure of the residual limb. The socket can then be designed for even weight distribution across the residual limb during weight bearing activities instead of developing high pressure on the stump, a typical occurrence with older socket design methods (Carroll & Sabolich, 1999; May, 1996). Contouring also ensures a secure fit around the residual limb, increasing the amputee's confidence in the security of the prosthesis (May, 1996).

The TranFem prosthetic device also has a knee joint component. The prosthetic knee joint functions to allow the amputee to sit or kneel, have smooth and controlled lower leg and foot movement during the swing phase of walking or running, and have stability during weight bearing. The knee joint component can be broken into two categories: sliding friction and hydraulic (also known as constant friction and variable friction, respectively). Both categories of knee components can either have swing phase or stance phase control or both swing and stance phase control. Swing phase control refers to having control over the rate of knee movement during the swing phase of walking. Stance phase control refers to the amount of stability obtained when weight is on the prosthesis (May, 1996). The constant friction knee components do not have a hydraulic unit. The hydraulic knee components have a cylinder filled with a synthetic oil that is located at the upper part of the lower leg that provides swing phase control (May, 1996). The hydraulic knee components are generally heavier and require more

maintenance than the sliding knee components. However, the hydraulic knee components respond better to varying gait speeds (May, 1996).

The pylon connects the socket or knee unit (TranFem) to the prosthetic foot. The pylon takes place of the tibia and fibula, making it responsible for transferring the weight load from the socket or knee unit to the prosthetic foot (Carroll & Sabolich, 1999; May, 1996). By emulating the muscles and tendons of the lower leg during movement, the pylon allows for vertical shock and torque absorption (Carroll & Sabolich, 1999). By acting as a dynamic component responsive to varying loading magnitudes, the pylon helps to reduce the occurrence of surface injury to the residual limb.

The prosthetic foot component attaches directly to the pylon. According to May (1996), the foot component is responsible for mimicking joint motion and muscle activity of the non-prosthetic foot. She states that all models of prosthetic feet provide plantar flexion, but few, e.g. split foot, provide inversion and eversion. During stance phase, muscle activity is mainly substituted for with varying degrees of plantar flexion, and swing phase passive dorsiflexion. The prosthetic foot is also responsible for absorbing forces generated at foot contact with the ground while providing a stable base of support (May, 1996).

Specialized dynamic response or energy conserving feet generate more propulsive force during terminal stance than nondynamic response feet (May, 1996). The nondynamic response feet, such as the solid ankle cushion heel (SACH™) and Single Axis™ prosthetic feet, do not provide propulsive force during terminal stance. Therefore, nondynamic response feet are most appropriate for people whose most strenuous activity is causal walking. As dynamic response or energy conserving feet do provide propulsion at terminal stance, these feet are more appropriate for individuals who want to participate in activities that require running and jumping (Carroll & Sabolich, 1999; May, 1996). According to May (1996) some popular dynamic feet are the Seattle™, Seattle Lite™, and Flex Foot™.

As physically active and highly skilled TranTib and TranFem individuals continue to request prostheses to allow the highest performance levels possible, the design of the prosthetic components are changed to accommodate the unique mechanical force requirements more strenuous activities being performed require. As such, studies have been conducted to explore what prosthetic design elements are most effective among the different prosthetic components.

Ehara et al. (1993) explored the energy-storing properties of 14 different prosthetic feet worn by one male TranTib amputee while walking. The participant performed the walking test 14 times while wearing a different prosthetic foot each time. The total energy about the ankle (energy stored plus the energy released) was used to categorize the prosthetic feet into high-, medium-, and low-total energy feet. Of the previously mentioned popular prosthetic feet, the Flex Foot™ was a high-energy foot, Seattle™ was a medium-energy foot, and SACH™ and Seattle Lite™ were low-energy feet.

The forces generated at foot contact with the ground are stored as energy in the foot component, reducing the impact force felt at the residual limb (Ehara et al., 1993). In agreement with this, the participant preferred the high-storing energy, but low-releasing energy feet (Seattle™ and SACH™ feet). Ehara et al. did not state why the subject preferred the high-storing energy, low-releasing energy feet as opposed to the other feet. It may be that the participant liked the high-storing energy feet because of the reduced impact felt on the residual limb, but felt he could not control the high-energy releasing feet, perhaps because of lack of practice with these feet. Certainly, the high-energy releasing feet are those worn by more active individuals.

Perry, Boyd, Rao, and Mulroy (1997) conducted a study comparing the mechanical attributes of the Single Axis™, Seattle Lite™, and Flex Foot™ on ten male TranTib participants who walked at self-selected speeds. A control group of ten male NonAmp participants was used for comparison. Each TranTib participant went through

the testing protocol while wearing each prosthetic foot. It was determined that the TranTib participants had a slower gait velocity than the NonAmp participants regardless of the prosthetic foot worn. In addition, the TranTib participants exhibited less knee flexion ($\bar{M} = 9^{\circ}$ - 12°) at weight acceptance phase while the NonAmp participants demonstrated an average knee flexion angle of 18° .

Perry et al. (1997) also discovered that the Seattle Lite™ and Flex Foot™ conditions produced longer rearfoot-only support times than the Single Axis™. It was surmised that the longer rearfoot-only support time delays the occurrence of foot flat, increasing the time the foot is in an unstable position. Perry et al. also surmised that the increased rearfoot-only support time delays forefoot contact and, as a result, decreases forward movement of the body during the weight acceptance phase of stance. Perry et al. also found that participants using the Single Axis™ had rapid plantar flexion and dorsiflexion during the rearfoot-only support phase that caused tibial instability.

Therefore, Perry et al. (1997) concluded that overall the dynamic prosthetic feet studied were not adequate in promoting stability and forward movement during weight acceptance of the stance phase for walking. It was also suggested that further development of the prosthetic foot components was needed to improve these problems.

Prosthetic and Running Literature

As the number of highly skilled and physically active TranTib and TranFem amputees increase, it is imperative that performance techniques and the influence of the prosthesis on the mechanics of performance techniques are understood. One activity that is becoming popular amongst the TranTib and TranFem athletes is running. In running, as in any activity in which the body is supported and propelled into the air via contact of the foot with the ground, the prosthesis becomes a substitute for the musculature and skeletal and articular structures lost in the amputation procedure. As such, the prosthetic foot component is responsible for absorbing impact forces and storing energy from ground contact and releasing the stored energy (Brouwer et al., 1989; Ehara et al., 1993).

In exploring the function of the SACH™ and Single Axis™ foot components for six children with a single limb TranTib amputation, the children's running mechanics were similar between the two foot components (Brouwer et al., 1989). Furthermore, it was observed that the participants had asymmetrical running stride kinematics and kinetics while wearing either prosthetic foot. The asymmetry was explained by an equal or longer step duration for the ProsL than the NProsL. The longer step duration lead to a significantly lower vertical ground reaction force for the ProsL than the NProsL. The asymmetrical running gait pattern also was attributed to lesser ankle angular displacement and muscle moments for the ProsL than the NProsL. This indicated that neither the SACH™ nor Single Axis™ foot components designed for walking gait were satisfactory substitutes for the natural movements of the ankle/foot complex that occur during running.

The evidence of asymmetrical running stride kinematics for TranTib and TranFem individuals appear to be influenced by the participants' running experience, level of amputation, running speed, distance run, and prosthesis worn during a given study. Enoka et al. (1982), Gavron and Dawson (1995), and Sanderson and Martin (1996) reported that TranTib participants had shorter ProsL running stride lengths than the NProsL. Ciapponi et al. (1999) and Wang et al. (1999) reported similar findings for elite male and female TranFem 100 m and 200 m sprinters, respectively. However, Ciapponi et al. (1999) and Wang et al. (1999) reported that elite male and female TranTib 100 m and 200 m sprinters had similar stride lengths for both the ProsL and NProsL, respectively.

Another asymmetrical pattern between NonAmp and TranTib and TranFem athletes is the amount of vertical displacement of the COM_B during the stance phase. The amount of knee flexion during the stance phase affects the vertical displacement of the COM_B. Sanderson and Martin (1996) reported that male TranTib athletes had less ProsL knee flexion than the knee of the NProsL during the running stance phase. Buckley (1999) reported that male NonAmp athletes had an average maximum knee flexion angle

of 144° while the male TranTib athletes had a maximum knee flexion angle of 143° and 138° for the NProsL and ProsL, respectively. The male TranFem athlete had a maximum knee flexion angle of 143° and 172° for the NProsL and ProsL, respectively. By not flexing the knee as much as the NonAmp athletes, the TranTib and TranFem athletes had less vertical displacement of the COM_B during the running stance phase. However, Gavron and Dawson (1995) reported that elite TranTib sprinters had a greater vertical displacement of the COM_B for the ProsL (3.90 cm) than the NProsL (3.23 cm). This can be attributed to a greater maximum knee flexion angle for the ProsL than NProsL. The contradictory findings of Buckley (1999) and Gavron and Dawson (1995) for TranTib runners may be attributed to the differences of ability of the participants.

Enoka et al. (1982) conducted a TranTib amputee running study to determine stride kinematics. The participants for this study were one female and nine male TranTib individuals. Enoka et al. reported that the participants had limited ankle range of motion for the prosthetic component compared to the NProsL ankle. It was surmised that in order to compensate for the lack of ProsL ankle range of motion, the participants increased the momentum contributed from the NProsL during the swing phase by increasing the range of motion about the hip (Enoka et al., 1982). This increase in hip range of motion helped to increase the time of the non-support phases initiated from the ProsL such that they were in a close range with the time of the non-support phases initiated from the NProsL (Enoka et al., 1982). In essence, the participants compensated for the lack of ProsL ankle range of motion by adjusting movement techniques of the NProsL.

In summary, from the findings of the running literature it has been demonstrated that many lower extremity amputee participants modify their running gait technique from NonAmp running gait technique to compensate for the constraints associated with the ProsL and prosthesis (Brouwer et al., 1989; Buckley, 1999; Ciapponi et al., 1999; Enoka et al., 1982; Gavron & Dawson, 1995; Sanderson & Martin, 1996; Wang et al., 1999). However, the compensatory actions used by individuals are not well understood, and may

be influenced by a combination of factors: skill level, level of amputation, running speed, distance run, and prosthesis worn. The mechanical characteristics unique to lower extremity amputee running gait may be an indication that performance techniques of other activities may also be modified. In the next section the current understanding of the mechanics of the long jump for elite NonAmp and lower extremity amputee athletes are described

Long Jump Literature

Approach Phase

The mechanical purpose of the approach phase is to generate as much horizontal velocity as possible that is controllable at takeoff and to get as close as possible to the edge of the takeoff board without stepping over it. The approach phase is broken into two sub-phases: initial and final. During the initial sub-phase of the approach, the athlete wants to generate maximum horizontal velocity controllable at takeoff. NonAmp athletes manipulate both stride length and stride frequency to increase horizontal velocity (Hay, 1993a) while TranTib participants exhibit different strategies to increase horizontal velocity (Enoka et al., 1982; Miller, 1981; Simpson et al., 1998). For TranTib running and long jump studies, several different velocity strategies have been observed. Simpson, Williams, Ciapponi, Wen, & Del Rey (2000) noted that for Paralympic long jump athletes, the constraints of the ProsL influenced how velocity was gained. Those long jump athletes who exhibited interlimb symmetry for stride kinematics also tended to increase running velocity by linearly increasing the stride lengths of both limbs. In contrast, those long jump athletes who displayed stride lengths and frequencies lower for the ProsL than the NProsL also tended to increase only the NProsL stride lengths and frequencies.

Simpson et al. (1998) reported that the majority of 1996 Paralympic TranFem long jump athletes increased horizontal velocity by increasing stride length, but not stride frequency. This is the only reported study known to date to explore how lower extremity amputee athletes increase horizontal velocity during a long jump approach.

During the final sub-phase of the approach, the mechanical purpose changes from generating horizontal velocity to preparing for takeoff. NonAmp long jump athletes perform either the 'traditional' or the 'gather' approach technique. The traditional technique is an approach technique in which the downward vertical displacement of the COM_B during the penultimate stride is not deliberately modified during the approach. This approach technique when compared to the gather technique minimizes the loss of horizontal velocity throughout the last two strides, but reduces the increase in vertical takeoff velocity (Ciapponi, 1996).

The gather technique is an approach technique in which the athlete deliberately drops the COM_B during the penultimate stride of the approach phase (Hay, 1993a; Hay & Nohara, 1990; Koh & Hay, 1990; Lees et al., 1993; Lees et al., 1994; Luhtanen & Komi, 1979; Tidow, 1990; Weidner & Dickwach, 1990). The athlete drops the COM_B during the penultimate stride by placing the touchdown foot farther in front of the COM_B making the penultimate stride longer than the previous and last strides of the approach (Hay, 1993a; Lees et al., 1994) and by not completely extending the support leg during the third-to-last stride of the approach support phase (Tidow, 1990).

Hay and Nohara (1990) conducted a study on the drop of the COM_B of elite NonAmp long jump athletes who used the gather technique. The women dropped their COM_B an average of 0.03 m while the men dropped their COM_B an average of 0.05 m from touchdown of the penultimate stride to touchdown of the last stride. At touchdown of the last stride and touchdown on the takeoff board, the women and men maintained the height of their COM_B . From touchdown on the takeoff board to takeoff the women elevated their COM_B 0.20 m and the men elevated their COM_B 0.26 m.

One technique used to drop the COM_B during the penultimate stride is making the penultimate stride longer than the previous approach stride by placing the foot farther in front of the COM_B at touchdown to the last stride of the approach (Hay, 1993a; Lees et al., 1994; Tidow, 1990). NonAmp athletes have been used to study the length of the penultimate and last stride in the gather technique. Hay and Nohara (1990) found that the

penultimate stride length was 1.27 m and 1.50 m for elite women and men athletes, respectively, while the last stride length was .92 m and .93 m for women and men, respectively. Lees et al. (1994) reported that during the penultimate stride, the lead leg contacted the ground in front of the COM_B increasing the penultimate stride length. The length of the last stride was manipulated due to the lack of full extension of the support leg and the lead leg contacting the ground near the COM_B (Tidow, 1990).

A longer penultimate stride than the previous stride length could be utilized by TranTib and TranFem athletes due to the degree of interlimb stride length asymmetry between the ProsL and NProsL that likely exists during running. As previously stated, there are conflicting reports on interlimb symmetry for stride lengths among running literature, perhaps because these studies varied from one another relative to the running speeds used, skill level of the participants, and prostheses worn (Buckley, 1999; Ciapponi et al., 1999; Enoka et al., 1982; Gavron & Dawson, 1995; Miller, 1981, Sanderson & Martin, 1996; Simpson et al., 1998; Wang et al., 1999).

For TranTib and TranFem long jump athletes, it was not clear what approach technique would typically be used by the higher skilled athletes. In an unpublished technical report, Simpson et al. (1997) reported that five out of ten TranTib athletes at the 1996 Paralympic Games exhibited a longer penultimate stride length than the previous stride, perhaps suggesting that the COM_B was lowered. In addition, Nolan and Lees (1999) reported that elite male TranFem athletes had a higher COM_B height compared to TranTib and NonAmp long jump athletes while TranTib compared to NonAmp long jump athletes, had similar COM_B height at touchdown onto the takeoff board. This suggests that the COM_B for the TranTib athletes had been lowered prior to touchdown onto the takeoff board. However, this finding may have been influenced by the height of the athletes or interparticipant variability. Furthermore, in contrast to the NonAmp long jump athletes, the TranTib and TranFem athletes continued to lower the COM_B during the initial takeoff phase. Nolan and Lees surmised that consequently, the TranTib and TranFem athletes had less time to develop upward vertical momentum. Therefore, it

appears that the COM_B of the TranTib and TranFem athletes was not sufficiently lowered prior to touchdown onto the takeoff board.

Whether the higher skilled athletes for this study would exhibit a lowered COM_B during the penultimate and/or last stride of the approach may be influenced by the mechanics of the ProsL. For some participants, maintaining a low COM_B during the last stride (ProsL = support phase limb) may not occur. This is based on observations that during running, the ProsL demonstrates less knee extensor moments generated during the support phase (Brouwer et al., 1989; Miller, 1987) less knee flexion positioning exhibited during all phases (Enoka et al., 1982; Gavron & Dawson, 1995; Sanderson & Martin, 1996), and less maximum hip extension at takeoff (Brouwer et al., 1989; Miller, 1987) compared to the NProsL.

Takeoff Phase

The mechanical purpose of the takeoff phase is to: (a) obtain vertical velocity while maintaining as much horizontal velocity as possible, (b) optimize the COM_B height at takeoff and (c) project the body into the air at an optimal takeoff angle of less than 45° (Hamill & Knutzen, 1995).

To either maintain horizontal velocity or augment the generation of vertical velocity during takeoff, two methods of placing the support leg on the ground or the takeoff board have been used by NonAmp long jump athletes, the ‘active landing’ and ‘height’ techniques (Bosco et al., 1975; Hay & Miller, 1985; Koh & Hay, 1991; Marino & Young, 1990). In the active landing technique, the athlete attempts to pull the touchdown foot backwards using a pawing action, causing the touchdown foot to be planted slightly in front of the COM_B at a velocity close to 0 m/s relative to the ground (Koh & Hay, 1990). When compared to a height landing technique, the backward sweeping action of the touchdown foot, helps reduce the loss of horizontal velocity of the athlete’s COM_B at touchdown by minimizing the anteroposterior braking ground reaction forces present at touchdown (Koh & Hay, 1990). As the touchdown foot lands slightly in front of the athlete’s COM_B , the COM_B can be pulled over the touchdown foot quickly,

thereby minimizing the amount of time the touchdown foot spends in the braking phase, and therefore, the braking impulse also is minimized (Bosco et al., 1975; Marino & Young, 1990). Consequently, this enables a minimal loss of horizontal momentum at touchdown.

During the execution of the height technique the takeoff foot is placed in front of the COM_B in a blocking manner. This blocking action produces a large anteroposterior braking ground reaction force and decreases horizontal takeoff velocity. Compared to the active landing technique, this action allows for a greater production of vertical takeoff velocity by increasing the duration the takeoff foot is on the takeoff board. However, the increased production of vertical takeoff velocity does not outweigh the loss of horizontal takeoff velocity. As a result long jump performance is not improved (Bosco et al., 1975; Hay & Miller, 1985; Koh & Hay, 1990; Marino & Young, 1990). Nelson and Zebas (1990) and Young and Marino (1984) found that the horizontal takeoff velocity was the more influential variable affecting long jump distance. As a result, the optimal landing technique would be the active landing technique.

While on the takeoff board, the amount of negative vertical impulse was less for the athletes that already had a lowered COM_B at touchdown onto the takeoff board than those who did not lower their COM_B until after touchdown onto the takeoff board (Lees et al., 1994; Lees et al., 1993). Consequently, by reducing the magnitude of vertical impulse below body weight, more vertical velocity potentially may be generated at takeoff (Lees et al., 1994; Lees et al., 1993). By minimizing the magnitude of vertical impulses below body weight while on the takeoff board, the reversal of vertical impulse below body weight to vertical impulse above body weight in order to generate vertical velocity prior to takeoff was lessened. The more time the athlete spends generating vertical impulse above body weight, the more vertical velocity can be generated at takeoff (Lees et al., 1994; Lees et al., 1993; Weidner & Dickwach, 1990).

Nolan and Lees (1999) reported that the TranFem long jump athletes that did not enter the takeoff phase with a lowered COM_B at touchdown onto the takeoff board had a

greater negative vertical velocity than the TranTib long jump athletes who did enter the takeoff phase with a lowered COM_B . They surmised that these athletes must then use a greater proportion of their vertical impulse to reverse the negative vertical velocity to positive vertical velocity prior to takeoff, thereby reducing the amount of positive vertical momentum gained.

When determining the optimal projection angle, the takeoff and landing heights of the COM of the object of interest must be considered. In the long jump the projection height of the COM_B is higher than the landing height of the COM_B . As a result, the optimum takeoff angle to achieve maximum horizontal distance is less than 45° (Hamill & Knutzen, 1995; Hay, 1986). Most NonAmp long jump athletes obtain a takeoff angle between 18° and 26° (Bosco et al., 1975; Dyson, 1986; Hay, 1986; Hay, 1993c; Jarver, 1972; Tidow, 1990; Unger, 1980; Weidner & Dickwach, 1990). Nolan and Lees (1999) reported mean takeoff angles of 21.0° and 18.4° for the TranTib and TranFem long jump athletes, respectively. This suggests that the average takeoff angle achieved by the lower extremity amputee long jump athletes has a similar range as the NonAmp long jump athletes.

Flight Phase

The mechanical purpose of the flight phase is to touch the sand as far as possible from the takeoff board and to control the body positioning so that during the landing phase, no part of the body will contact the sand behind the initial contact point (i.e., behind the landing point of the foot closest to the takeoff board).

Thus, athletes use one of three flight techniques: sail, hang, or hitch-kick. For a description of each flight technique see Appendices A-C. El Khadem and Huyck (1966) surmised that the flight technique performed depends on the amount of time spent in the air. The hitch-kick flight technique takes longer to perform than the hang or sail flight technique, so the athlete must be in the air long enough to perform the hitch-kick flight technique. Elite NonAmp athletes tend to use the hitch-kick flight technique (Hay, 1986;

Weidner & Dickwach, 1990) while all flight techniques and the sail flight technique were reported as being performed among Paralympic TranTib and TranFem athletes, respectively (Simpson et al., 1997).

Landing Phase

The mechanical purpose of the landing phase is to safely stop movement of the body, land as far from the takeoff board as possible without subtracting from the distance of the jump by reaching or falling backwards. Simpson et al. (1997) reported that the TranTib and TranFem long jump athletes tended to fall laterally to one side or the other upon landing. Seven out of 12 TranTib and all of the TranFem athletes fell toward the side opposite their ProsL. They postulated that the athletes were attempting to reduce the impact forces to the residual limb. They also surmised that because the ProsL length is longer compared to the NProsL, the ProsL would contact the ground first, creating a torque in the frontal plane that would cause the body to rotate laterally, i.e., to fall toward the NProsL side. Simpson et al. also reported that four of the 22 TranTib athletes appeared to fall forward over their feet instead of using the technique of flexing the lower extremities to cause the body to move towards the feet at contact with the ground. It was surmised that this could have been due to an inability to flex the ProsL or to maintain sufficient stability of the residual limb within the socket. However, it is also possible that those athletes fell forward due to improper technique that occurred prior to landing.

CHAPTER III

A KINEMATIC ANALYSIS OF TECHNIQUES USED BY ELITE AMPUTEE LONG
JUMP ATHLETES. PART I: TRANSTIBIAL CLASSIFICATION²

² Ciapponi, T. M. and Simpson, K. J. to be submitted to Journal of Applied Biomechanics

ABSTRACT

The transtibial (TranTib) amputee long jump athletes have limited biomechanical research conducted to determine the performance techniques used by athletes that jump the farthest. As such, the purpose of this study of elite TranTib athletes was to determine how the kinematic characteristics exhibited during long jump performances varied between higher and lower skilled long jump athletes.

All of the long jump performances of the women's long jump ($n = 4$) and the men's long jump and pentathlon competitions ($n = 6$) were videotaped for analysis at the 1998 Ultimate Challenge Track and Field Invitational and 1999 National Summer Games, respectively. The farthest legal jump for each participant was selected for analysis. Due to the small sample sizes, non-parametric statistics (Kolmogorov-Smirnov, Mann-Whitney U, and chi-square tests) were used to analyze technique based hypotheses ($p < 0.05$).

For the TranTib athletes, only two comparisons were statistically significant. However these findings were influenced by gender. The men dropped while the women raised the body's COM (COM_B) during the penultimate stride of the approach. Thus, it is not known if dropping the COM_B is advantageous for the TranTib athletes. The following performance techniques were used by most of the higher skilled TranTib athletes:

1. Placed the takeoff foot onto the takeoff board in a backward sweeping motion.
2. Performed the flight technique appropriate for the variable flight time.
3. Achieved a small lower leg landing angle by the athletes having their legs extended about the knee joints and flexing the trunk about the lower vertebral joints causing a reaction of hip flexion.

Introduction

Since the first Olympic and Paralympic Games, the long jump has become a highly competitive track and field event where the margin of victory for a gold medal can be as little as 0.01 m. Therefore, during each jump, athletes attempt to use movement techniques that capitalize on the physics underlying the production of a maximal length jump.

Numerous biomechanical studies have been conducted to determine optimal performance techniques that long jump athletes without physical limitations use to produce a maximal length jump (for review, see Hay, 1986; Hay, 1993a). However, for athletes with physical limitations, specifically lower extremity amputations, the biomechanical research available regarding optimal long jump performance techniques and the underlying biomechanics are limited (Nolan & Lees, 1999; Simpson, Williams, Ciapponi, Wen, Nance, & Valleala, 1998; Williams, Simpson, & Del Rey, 1997). While the mechanics of each phase of the long jump (approach, takeoff, flight, and landing) play an integral role in producing a maximal length jump, the only understanding of the mechanics of transtibial (TranTib) performance techniques has come from kinematic studies of selected aspects of the approach (Simpson et al., 1998; Williams et al., 1997) and the takeoff phases (Nolan & Lees, 1999).

Furthermore, it is not known whether TranTib athletes should use the same movement techniques as non-amputee (NonAmp) athletes, i.e., make similar use of the underlying biomechanics. There is a loss of musculature and neuromuscular control after a lower extremity amputation (Enoka, Miller, & Burgess, 1982; Martin & Sanderson, 1998), and the characteristics of the prosthesis used during maximal effort running and long jump competitions are different than a non-prosthetic limb (NProsL), e.g., less mechanical energy is available during the propulsive phase of running and different inertial characteristics exist (Brouwer, Allard, & Labelle, 1989; Ehara, Beppu, Nomura, Kunimi, & Takahashi, 1993). Subsequently, compared to elite NonAmp performers, it is likely that optimal performance techniques for elite TranTib performers will differ.

It is anticipated that, for this study of TranTib long jump athletes, performance techniques will vary among athletes. In addition to the usual factors that contribute to the skill level of a given athlete, e.g., training, differences among TranTib long jump athletes also exist for factors unique to the prosthetic limb (ProsL), e.g., location of amputation and muscle energetics. (Brouwer et al., 1989; Ehara et al., 1993). Therefore, all of these factors will influence the performance characteristics distinguishing higher skilled athletes (i.e. those who jump farther) from lesser skilled athletes.

Therefore, to generate a more comprehensive understanding of optimal performance techniques used by TranTib long jump athletes, the purpose of this study was to determine how the kinematic characteristics exhibited by higher skilled athletes varied from the lesser skilled athletes. In regards to comparing higher skilled versus lesser skilled athletes, the following questions were asked: (a) what movement techniques were used to create optimal vertical and near maximal takeoff velocities during the approach and takeoff phases; (b) are the flight phase movements appropriate for positioning the body for an optimal landing, given the flight time; and (c) what movement techniques are exhibited during the landing phase that allow the athlete to maximize the landing distance?

There are several factors that influence the magnitudes of horizontal and vertical velocities at takeoff. The amount of horizontal velocity at takeoff is constrained by the maximal amount of velocity that the athlete can generate and control during the last two strides³ of the approach while the athlete positions the body for the takeoff phase. Also, to generate vertical velocity during the takeoff phase, particular movement techniques are performed not only during the takeoff phase, but also during the approach phase as well. However, use of these techniques also result in generating negative horizontal impulses that reduce horizontal takeoff velocity.

³ A running stride is defined as from touchdown of one foot to touchdown of the other foot. A running cycle is composed of two running strides or from touchdown of a given foot until the next touchdown of the same foot (Hay, 1993b).

In order to position the body in preparation for generating the vertical impulse needed to produce the optimal magnitude of vertical takeoff velocity, two techniques are utilized by highly skilled NonAmp athletes: (a) lowering the body's center of mass (COM_B) prior to touchdown onto the takeoff board (Koh & Hay, 1990) and (b) placing the takeoff foot onto the takeoff board while the foot is moving near 0 m/s relative to the ground (Koh & Hay, 1990; Marino & Young, 1990; McLean, 1995). First, the athlete must lower the COM_B during the last two strides of the approach in order to start the takeoff phase with a low COM_B height. In this manner, the athlete can use the entire takeoff phase to generate upward vertical momentum via the vertical ground reaction force impulse generated during the takeoff phase (Luhtanen & Komi, 1979). NonAmp athletes tend to lower the COM_B primarily during the penultimate stride of the approach and do so by not completely extending off the support leg during the support phase (Tidow, 1990) and by ending the penultimate stride with the touchdown foot contacting the ground farther in front of the COM_B than the previous stride (Hay, 1993a; Lees, Graham-Smith, and Fowler, 1994), thereby making the penultimate stride longer than the previous stride lengths. This action may also create a longer penultimate stride than last stride of the approach. During the last stride that ends at touchdown onto the takeoff board, the height of the COM_B is then either maintained or is lowered further by the time touchdown onto the takeoff board occurs (Hay, 1993a; Hay & Nohara, 1990; Koh & Hay, 1990; Lees, Fowler, & Derby, 1993; Luhtanen & Komi, 1979; Tidow, 1990; Weidner & Dickwach, 1990).

The approach technique in which the COM_B is deliberately lowered during the penultimate stride is termed the 'gather approach' technique (Hay, 1993c; Hay & Nohara, 1990; Koh & Hay, 1990; Lees et al., 1993; Luhtanen & Komi, 1979; Tidow, 1990; Weidner & Dickwach, 1990) (see Figure 2). Although this technique promotes a high generation of vertical velocity during the takeoff phase, a greater loss of horizontal velocity also concurrently occurs (Koh & Hay, 1990). A second approach technique, the 'traditional approach', is performed when the COM_B is not dropped during the

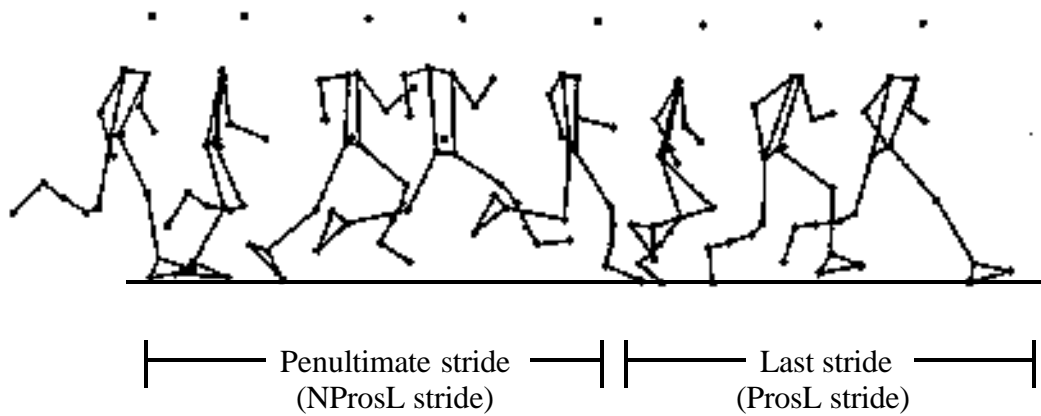


Figure 2. The penultimate stride and last stride of the gather approach technique. The triangular-shaped foot is the non-prosthetic (NProSL) foot.

penultimate stride of the approach. Athletes may maintain the COM_B position or drop the COM_B during the last stride or after touchdown onto the takeoff board to prepare for takeoff. For NonAmp athletes, this approach technique minimizes the loss of horizontal velocity throughout the last two strides, but less vertical takeoff velocity is generated compared to that generated during the gather technique (Ciapponi, 1996).

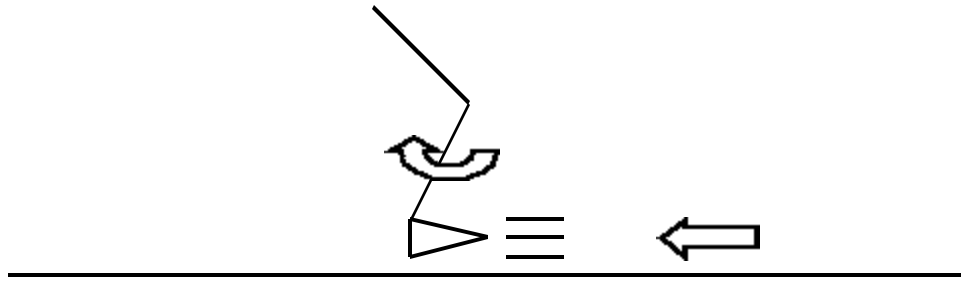
For TranTib long jump athletes, it was not clear what approach technique would typically be used by the higher versus lower skilled athletes. In an unpublished technical report, Simpson, Williams, Ciapponi, Wen, and Nance (1997) reported that five out of ten TranTib athletes at the 1996 Paralympic Games exhibited a longer penultimate stride length than the previous stride, perhaps suggesting that the COM_B of some athletes was lowered. In addition, Nolan and Lees (1999) reported that elite male TranTib compared to NonAmp long jump athletes had similar COM_B height at touchdown onto the takeoff board. This suggests that the COM_B had been lowered prior to touchdown onto the takeoff board. However, this finding may have been influenced by the height of the athletes or interparticipant variability. Furthermore, in contrast to the NonAmp long jump athletes, Nolan and Lees noted that the TranTib athletes continued to lower the COM_B during the takeoff phase. Nolan and Lees surmised that, consequently, the TranTib athletes had less time to develop upward vertical momentum. Therefore, it appears that the COM_B of the TranTib athletes was not sufficiently lowered prior to touchdown onto the takeoff board.

In addition, whether the higher skilled athletes for this study would exhibit a lowered COM_B during the penultimate and/or last stride of the approach may be influenced by the mechanics of the ProsL. For some participants, maintaining a low COM_B during the last stride (ProsL = support phase limb) may not occur. This is based on observations that during the support phase of running, the ProsL of non-athletes demonstrate less knee extensor support phase moments (Brouwer et al., 1989; Miller, 1987), less knee flexion during all phases (Enoka et al., 1982; Gavron & Dawson, 1995; Sanderson & Martin, 1996), and less maximum hip extension at takeoff (Brouwer et al.,

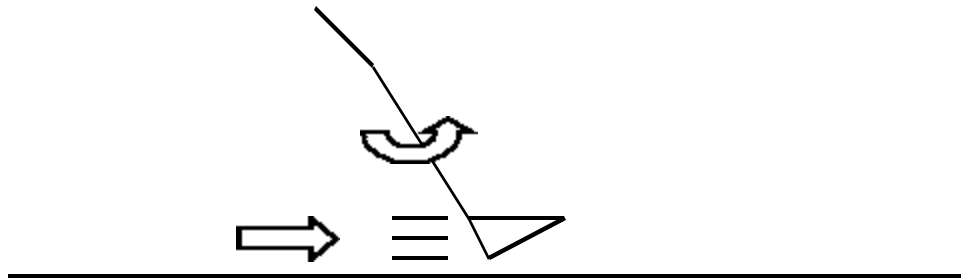
1989; Miller, 1987) compared to the NProsL. As such, it was expected that for this study the higher skilled athletes would exhibit a gather approach technique, i.e., they would demonstrate a negative vertical displacement of the COM_B of 0.03 m or more (Hay & Nohara, 1990) during the penultimate stride of the approach. Athletes who did not exhibit a minimum of -0.03 m vertical displacement were grouped as performing a traditional approach technique. It was also expected that the athletes that performed a gather approach technique would have a greater decrease in horizontal velocity and a greater increase in vertical velocity from touchdown onto the takeoff board until the instant of takeoff than the athletes that performed the traditional approach technique.

The second strategy that influences vertical and horizontal takeoff velocity is the method used to place the takeoff foot onto the takeoff board. Two methods of placing the support leg onto the takeoff board, the ‘active landing’ and the ‘height’ techniques, have been used to either maintain horizontal velocity during the takeoff phase or to augment the generation of vertical takeoff velocity (see Figure 3a-b, respectively). The active landing technique is performed by the athlete pulling the touchdown foot backwards using a pawing action. This action places the touchdown foot slightly in front of the COM_B at a velocity close to 0 m/s relative to the ground and allows the athlete’s COM_B to quickly pass over the takeoff foot (Koh & Hay, 1990). For the height technique, the athlete places the touchdown foot anterior to the body’s COM in a ‘blocking manner’. In contrast to the height technique, the active landing technique actions result in less horizontal braking impulse, but also causes less time to generate vertical impulse during the takeoff phase (Marino & Young, 1990; McLean, 1995).

It was expected that for this study, the higher skilled TranTib athletes would perform an active landing technique to take advantage of maintaining horizontal velocity and because the NProsL is the limb that performs the action of the active landing technique. It was predicted that those athletes that performed an active landing technique would also be on the takeoff board for a shorter duration of time, have less of a decrease



(b) Active landing technique



(b) Height landing technique

Figure 3. The (a) active landing and (b) height landing techniques.

in horizontal velocity and less of an increase in vertical velocity during the takeoff phase than the athletes that performed a height technique.

Of most interest for the flight and landing phases was to determine how the athletes maximized their jump distance while being able to land safely. An athlete wants to land with the legs near parallel with the knees slightly bent and the hips flexed, bringing the trunk close to the thighs via hip flexion (Hay, 1993a) (see Figure 6). For the landing phase, Simpson et al. (1997) reported that the TranTib long jump athletes tended to fall laterally toward the NProsL side upon landing. They postulated that the athletes were attempting to reduce the impact forces to the residual limb. They also surmised that because the ProsL length is longer compared to the NProsL, the ProsL would contact the ground first, creating a torque in the frontal plane that would cause the body to rotate laterally, i.e., to fall toward the NProsL side. Simpson et al. also observed that the entire body of the TranTib athletes appeared to rotate forward as one unit over their feet, causing them to land on their hands instead of flexing their lower extremities so the body moves towards the feet at contact with the ground. However, it is also possible that those athletes fell forward due to improper technique that occurred prior to landing. Based on the findings of Simpson et al. it was expected that some of the TranTib and TranFem long jump athletes would not be in an optimal landing position, thereby causing them to fall to one side or the other or to fall forward over their feet upon landing.

Methodology

Data Collection

All of the long jump performances of the female ($n = 4$) and male ($n = 6$) TranTib long jump and pentathlon competitions at the 1998 Ultimate Challenge Track and Field Invitational and 1999 National Summer Games, respectively, were videotaped for analysis. Table 1 depicts performance data for all participants. As the cameras used and the camera locations varied among the long jump events, the camera positioning and other related information are shown in Table 2 for the various camera configurations.

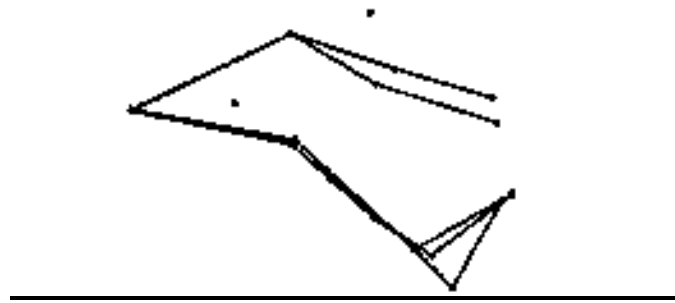


Figure 6. Ideal landing position.

Table 1

Competition, Distance Jumped and CompetitionResults for All Participants

| Event and participant no. | Competition | Distance jumped (m) | Place in event |
|------------------------------|-----------------------|------------------------|-------------------|
| Women's | Ultimate Challenge | | |
| 1 | | 4.11 | 1 |
| 2 | | 3.87 | 2 |
| 3 | | 3.80 | 3 |
| 4 | | 3.62 | 4 |
| Men's | U.S. Nationals | | |
| 5 | | 6.24 | 1 |
| 6 | | 5.69 | 2 |
| 7 | | 5.41 | 3 |
| Men's Pentathlon | U.S. Nationals | | |
| 8 | | 5.38 | 1 |
| 9 | | 5.12 | 2 |
| 10 | | 4.45 | 3 |

Table 2Camera Configurations

| Event | Camera number | Camera distance to subjects (m) | Field of view (m) | Calibration marker Length (m) | Phases captured |
|--------------------|---------------|---------------------------------|-------------------|-------------------------------|--|
| Women ^a | 1 | 30.60 | 16.00 | 3.74 | Approach: last 2 strides Takeoff, flight, and landing |
| Men | 2 | 18.87 | 8.77 | 4.54 | Approach: last 2 strides |
| | 3 | 17.97 | 10.76 | 4.54 | Takeoff, flight, and landing |
| Pentathlon | 2 | 18.15 | 8.45 | 4.54 | Approach: last 4 strides |
| | 3 | 15.20 | 9.29 | 4.54 | Takeoff, flight, and landing |

Note. Camera #1 = Panasonic™ (sampling rate = 60 Hz.; exposure time = 0.001 s);

Cameras #2 - #3 = Peak Performance Technology™ (sampling rate = 120 Hz.; exposure time = 0.002 s).

^aOnly one camera used due to limited unobstructed view.

Data Reduction

The farthest legal jump for each participant was selected for analysis. The Peak Motus32 Motion Measurement™ system (v. 4.3.3) was used to digitize an 18-point model of the body. The points digitized for the prosthesis are depicted in Figure 7. The raw data were then smoothed using a quintic spline (Jackson, 1979). Velocities were calculated using a forward-difference algorithm for the first point, a second-order central difference algorithm for the second point, and a backward-difference algorithm for the remaining points (Peak Performance Technologies™, 1998).

Anthropometric Measurements

To generate the COM_B coordinates, the COM of all of the body's segments except the residual limb and the prosthesis were generated using the gender specific regression equations of Plagenhoef (1983). The computation of the COM of the prosthesis (see Appendix D⁴) was based on the following: (a) the socket of the prosthesis was modeled as an elliptic paraboloid; (b) the lower leg and foot components were modeled as a bendable L-shape made up of two rectangular parallelepipeds with uniform density, composition, width, and thickness throughout the lower leg and foot components.

Quantities Generated

To determine if the athletes that performed the gather approach technique lowered the COM_B by increasing the length of the penultimate stride, the length of the penultimate and third-to-last and last strides of the approach were compared. To eliminate the possibility that the interlimb stride length asymmetry influenced stride length differences among the last three strides of the approach, the percent contribution of the third-to-last and penultimate strides to their respective running cycles was calculated. For the pentathlon athletes, the only athletes for which four strides were videotaped, the stride lengths of the fourth-to-last and third-to-last strides were added together to define the first running cycle. The stride lengths of the penultimate stride and last stride were

⁴ Appendix D is located at the end of the dissertation.

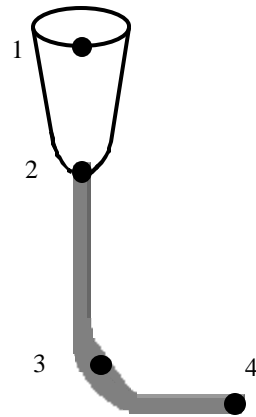


Figure 7. The points digitized for the prosthesis: (1) top of socket, (2) bottom of socket, (3) ankle, and (4) toe.

added together to define the second running cycle (see Figure 8). The two running cycle lengths were compared to determine if the second running cycle length was longer than the first running cycle length. If there was a significant difference in the running cycle lengths, the percentage that each stride contributed to the running cycle was determined. The percentage of the fourth-to-last stride and the penultimate stride were then compared to determine if the penultimate stride was longer than the fourth-to-last stride. For all the participants, the lengths of the penultimate and last strides were compared.

The horizontal velocity of the takeoff foot's COM was compared to the horizontal velocity of the COM_B for the instant just prior to touchdown onto the takeoff board to determine if the athlete performed an active landing or height technique (Koh & Hay, 1990). The landing technique at touchdown on the takeoff board was classified as active if the horizontal velocity of the COM of the foot was less than the horizontal velocity of the COM_B and the takeoff foot was moving in a negative direction.

The lower leg landing angle (see Figure 9) was used to determine if the athletes were able to attain and maintain appropriate body positioning to keep the body in the air as long as possible and to contact the ground safely and effectively.

For the temporal quantities, time on the takeoff board was defined as the time from the first field the takeoff foot contacted the takeoff board until the last field that the takeoff foot was on the takeoff board. Flight time was calculated from the first field after the takeoff foot left the takeoff board until the first field the athlete touched the sand.

Data Analysis

Due to the small sample size, non-parametric statistics were used to analyze the data (Siegel & Castellan, 1988). SPSS (v. 9) was used to calculate the statistics. To determine if TranTib athletes lowered their COM_B from the penultimate stride to the last stride and/or performed a penultimate stride length longer than the third-to-last and last strides of the approach a Kolmogorov-Smirnov (KS) test was used. To compare the values of variables between the gather versus the traditional approach technique subgroups, and, similarly, to compare the variables of the landing technique subgroups

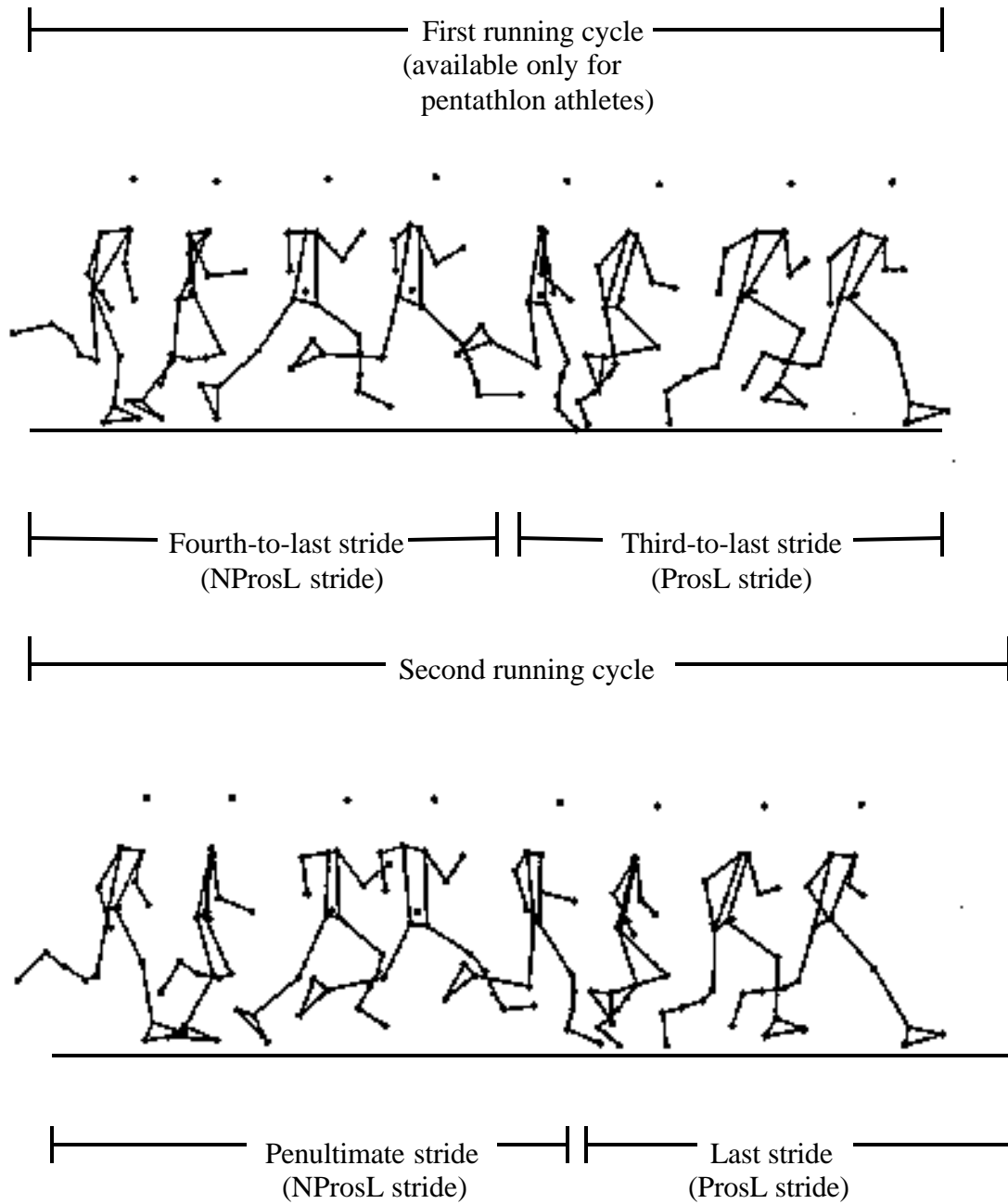


Figure 8. The last four strides of the approach and the running cycles. The triangular-shaped foot is the non-prosthetic (NProSL) foot.

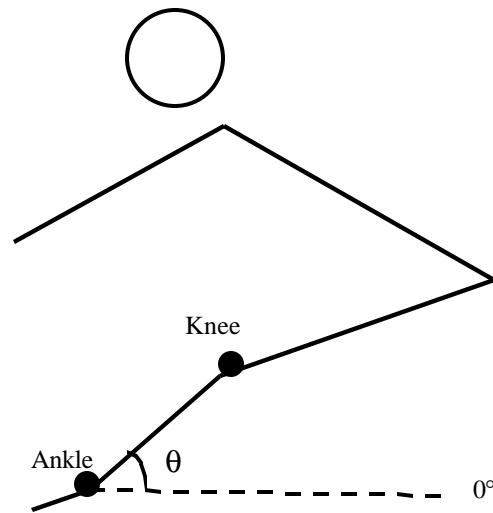


Figure 9. The lower leg landing angle.

and the flight technique subgroups, a Mann-Whitney U test was used. A chi-square test was used to determine if there were differences among flight techniques for the frequency of athletes that used a given flight technique. All statistical procedures were considered significant if $p < 0.05$.

Results

Only two comparisons were found to be statistically significant: (a) the distance jumped between the athletes that performed a gather versus traditional approach technique and (b) the flight time between the athletes that performed the hitch-kick versus the sail flight technique. This was expected for the Mann-Whitney U tests, as there were few participants ($n = 1$ to 5) in a given subgroup. Also, high interparticipant variability for running variables has been reported in studies of TranTib athletes (Gavron & Dawson, 1995; Nolan & Lees, 1999; Simpson et al., 1998; Simpson, Williams, Ciapponi, Wen, & Del Rey, 2000). As such, the individual data are of more interest than group data.

The first question of interest was to determine if there were distinguishable skill level differences for the kinematics used to generate horizontal and vertical takeoff velocity. It was hypothesized that lowering the COM_B during the penultimate stride (gather approach technique) would result in greater decreases in horizontal velocity and greater increases in vertical velocity during the takeoff phase compared to performing the traditional approach technique. The vertical displacement of the COM_B during the penultimate stride ranged from -0.06 m to 0.12 m, demonstrating the variability among participants. Four and six athletes exhibited positive and negative displacement, respectively (see Figures 10a-b). All of the athletes that raised the COM_B during the penultimate stride lowered the COM_B during the last stride of the approach. The five athletes that dropped the COM_B 0.03 m or more were categorized as performing the gather approach technique while the remaining five athletes were categorized as performing the traditional approach technique.

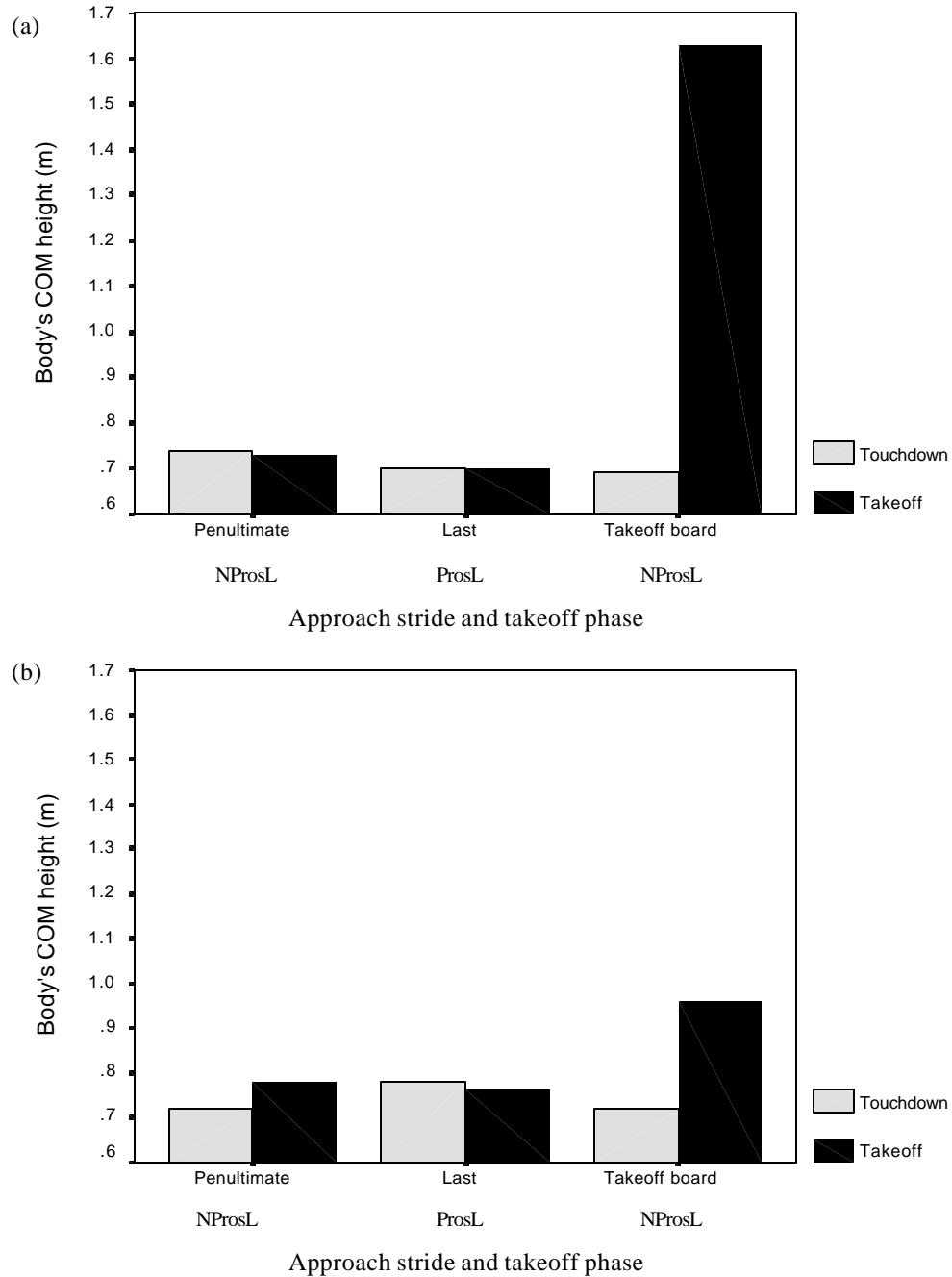


Figure 10. Body's COM height at touchdown and takeoff of the support phases of the last two strides and the takeoff phase. Representative participants are shown that exhibited vertical displacement of the penultimate stride that was: (a) negative (Participant 6) and (b) positive (Participant 4). The support phase limb is identified as the non-prosthetic (NProSL) or prosthetic (ProSL) limb.

One method for lowering the COM_B is to make the penultimate stride longer than the third-to-last and last strides by placing the touchdown foot farther in front of the COM_B than the previous and last strides, (Hay, 1993a; Lees et al., 1994). For the men's pentathlon ($n = 3$), the only group for which two running cycle data were available, there was no significant difference found in the running cycles lengths or the percent contribution of the third-to-last stride and penultimate stride to their respective running cycles. Overall, two pentathlon athletes had a longer penultimate stride while one athlete had a shorter penultimate stride than third-to-last stride (see Figure 11a).

When comparing the stride lengths of the penultimate stride and last stride of the approach, five athletes had a longer penultimate stride, although the difference between the stride lengths varied considerably from 0.02 m to 0.28 m. Five athletes had a shorter penultimate stride, with the difference between stride lengths ranging from -0.05 m to -0.18 m (see Figure 11b).

The traditional approach technique minimizes the loss of horizontal velocity throughout the last two strides, but less vertical takeoff velocity is generated compared to that generated during the gather technique (Ciapponi, 1996). The five athletes that performed the gather versus the five athletes that performed the traditional approach technique lost more horizontal velocity (range = 1.01 m/s to 2.49 m/s and 0.22 m/s to 1.04 m/s, respectively), and gained more vertical velocity (range = 1.98 m/s to 3.37 m/s and 2.02 m/s to 2.88 m/s, respectively) during the takeoff phase (see Figure 12a-b). A significant difference between the athletes performing a gather versus those who performed a traditional approach technique for the distance jumped was detected (see Table 3). The athletes that performed a gather approach technique jumped farther and had more horizontal takeoff velocity than the athletes that performed a traditional approach technique. While there was no significant difference found between the vertical takeoff velocity for the athletes performing a gather versus a traditional approach technique (see Table 3), the athletes that performed the gather approach technique tended to generate more vertical takeoff velocity than the athletes that performed a traditional approach

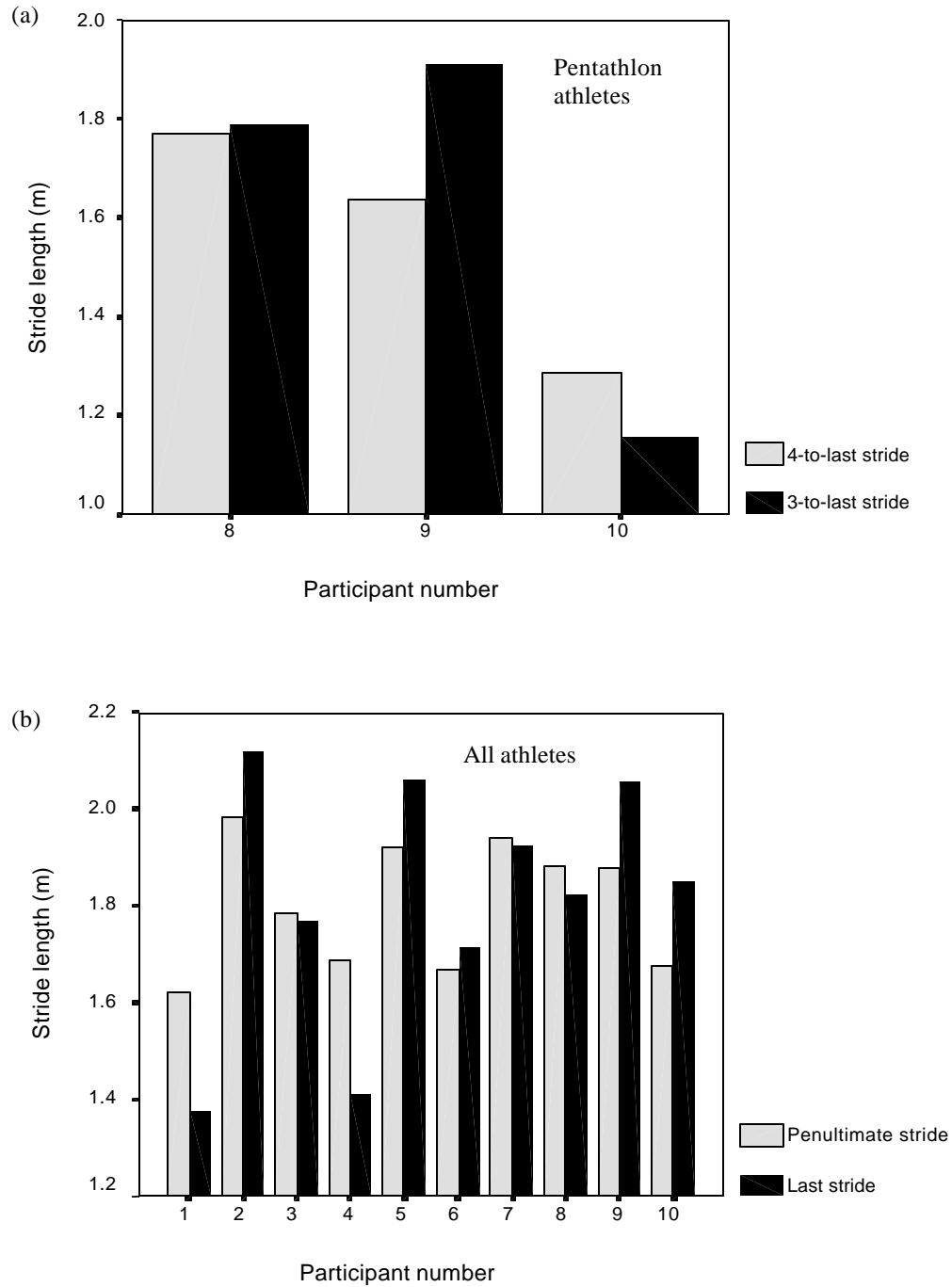


Figure 11. (a) The stride lengths for the first running cycle of the 3 men's pentathlon athletes and (b) the stride lengths for the second running cycle for each participant.

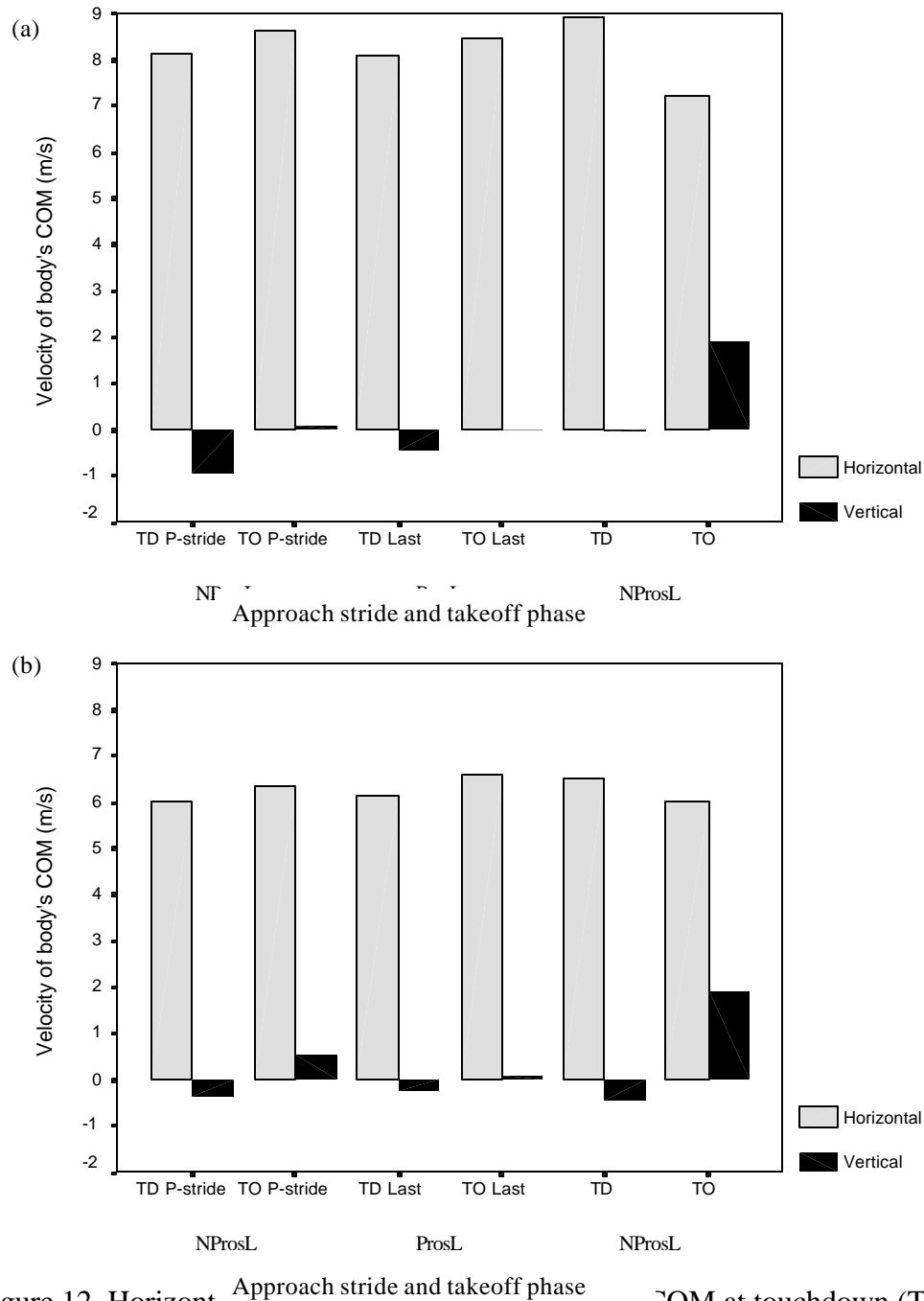


Figure 12. Horizontal COM at touchdown (TD) and takeoff (TO) for the penultimate (P-stride) and last stride of the approach and the takeoff phase. The graphs depict representative participants that exhibited; (a) an active landing (Participant 6) and (b) height (Participant 4) technique. The support phase limb is identified as the non-prosthetic (NProSL) or prosthetic (ProSL) limb.

Table 3

Individual Participant Values for Athletes Performing Gather (n = 5) and Traditional (n = 5) Approach Techniques

| Variable | Participants | | | | | | | | | |
|--|------------------|-------|------|-------|------------------|-------|-------|-------------------|-------|-------|
| | Women | | | | Men | | | | | |
| | <u>Long jump</u> | | | | <u>Long jump</u> | | | <u>Pentathlon</u> | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Gather approach technique (Y/N) | N | N | N | N | Y | Y | N | Y | Y | Y |
| Distance jumped (m) | 4.11 | 3.81 | 3.80 | 3.62 | 6.24 | 5.69 | 5.41 | 5.38 | 5.12 | 4.45 |
| Change in COM _B velocity _{takeoff phase} = $V_{\text{end}} - V_{\text{start}}$ (m/s): | | | | | | | | | | |
| V _x | -1.04 | -0.49 | 0.41 | -0.22 | -1.39 | -1.71 | -2.49 | -1.47 | -1.01 | -1.43 |
| V _y | 2.02 | 2.88 | 2.39 | 2.15 | 3.21 | 1.98 | 3.37 | 2.72 | 2.69 | 3.08 |

Note. Gather approach technique = “Y” when the body’s COM vertical displacement is –0.03 m or greater during the penultimate stride of the approach.

technique. However, for this study, all of the athletes that performed the gather approach technique were men and the athletes that performed the traditional approach technique were all women plus the third place male.

It was hypothesized that having negative horizontal velocity of the takeoff foot relative to the COM_B ($v_{rel\ ft}$) just prior to touchdown onto the takeoff board (active landing technique) would result in less time on the takeoff board and less of a decrease in horizontal velocity and less of an increase in vertical velocity during the takeoff phase compared to performing the height technique. Nine out of the ten athletes performed an active landing technique, with $v_{rel\ ft}$ values ranging from -0.50 m/s to -4.31 m/s (see Table 4). The remaining athlete was categorized as performing a height technique (Participant 4 $v_{rel\ ft} = 0.20$ m/s). This athlete, the lowest skilled female athlete, as well as the lowest skilled male athlete, had the longest time on the takeoff board. The athletes that performed an active landing technique tended to have a greater decrease in horizontal velocity and a greater increase in vertical velocity during the takeoff phase than the athlete that performed a height technique.

For the flight phase, there was no significant difference ($p = 0.74$) found for the number of athletes performing the different flight techniques ($n = 4$ and 5 for the hitch-kick and sail flight technique, respectively), although no athletes performed the hang flight technique (see Table 5) (no data for Participant 1; she stopped performing during mid-flight). It was hypothesized that the flight technique performed would be directly related to the flight time. As a group, the athletes that performed the hitch-kick had a significantly longer flight time ($p = 0.03$) than the athletes that performed the sail flight technique. However, there were two exceptions. Participant 10 performed the hitch-kick although his flight time was the same or shorter than Participants 9 and 7, respectively, who performed the sail flight technique.

The lower leg landing angle was used to determine if the athletes were able to attain and maintain appropriate body positioning to keep the body in the air as long as possible and to contact the ground safely and effectively. Between the flight technique

Table 4

Individual Participant Values for Athletes Performing Active Landing (n = 9) and Height (n = 1) Landing Techniques

| Variable | Participants | | | | | | | | | |
|---|------------------|-------|-------|------|------------------|-------|-------|-------------------|-------|-------|
| | Women | | | | Men | | | | | |
| | <u>Long jump</u> | | | | <u>Long jump</u> | | | <u>Pentathlon</u> | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| V_x of takeoff foot relative to V_x of body's COM (m/s) | -0.50 | -3.64 | -0.55 | 0.20 | -1.77 | -1.12 | -3.44 | -4.31 | -3.15 | -2.16 |
| Active landing (Y/N) | Y | Y | Y | N | Y | Y | Y | Y | Y | Y |
| Time on takeoff board (s) | 0.13 | 0.15 | 0.13 | 0.17 | 0.14 | 0.12 | 0.16 | 0.15 | 0.14 | 0.17 |
| Takeoff variables: | | | | | | | | | | |
| V_x of body's COM (m/s) | 4.83 | 5.98 | 5.56 | 6.27 | 8.32 | 7.22 | 7.13 | 7.52 | 7.90 | 6.83 |
| V_y of body's COM (m/s) | 1.92 | 2.27 | 1.88 | 1.70 | 2.47 | 1.95 | 2.39 | 2.41 | 1.91 | 2.17 |

Note. Active landing = “Y” when V_x takeoff foot – V_x of body's COM is negative.

Table 5

Individual Participant Values for Athletes Performing Hitch-Kick (n = 4) and Sail (n = 5) Flight Techniques and Landing Position

| Variable | Participants | | | | | | | | | |
|-----------------------------|------------------|------|------|------|------------------|------|------|-------------------|------|------|
| | Women | | | | Men | | | | | |
| | <u>Long jump</u> | | | | <u>Long jump</u> | | | <u>Pentathlon</u> | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Flight technique | -- | S | S | S | HK | HK | S | HK | S | HK |
| Flight time (s) | -- | 0.53 | 0.50 | 0.45 | 0.65 | 0.66 | 0.59 | 0.65 | 0.55 | 0.55 |
| Lower leg landing angle (°) | -- | 45 | 69 | 47 | 52 | 6 | 6 | 7 | 7 | 6 |
| Fell to one side (Y/N) | -- | N | N | N | Y | N | N | N | Y | N |

Note. S = sail flight technique. HK = hitch-kick flight technique. -- means data not obtained.

subgroups, there were no significant differences for the lower leg landing angle or distance jumped (see Table 5). The athletes that performed the sail tended to have a greater lower leg landing angle and not jump as far as the athletes that performed the hitch-kick flight technique. Also, two participants, the longest (Participant 5) and the fifth longest jump male (Participant 9) athletes fell to the NProSL side after flexing the lower extremities bringing the body toward their feet upon landing. Participant 5 also had the second largest lower leg landing angle which may have attributed to falling to the NProSL side after landing.

Discussion

To understand the kinematic characteristics used by TranTib athletes, particularly those used by the higher skilled athletes in comparison to those exhibiting by lower skilled athletes, three questions were asked: (a) what movement techniques are used to create optimal vertical and near maximal horizontal takeoff velocities during the approach and takeoff phases; (b) are the flight phase movements appropriate for positioning the body for an optimal landing, given the flight time, and (c) what movement techniques are exhibited during the landing phase that allow the athlete to maximize the landing distance?

For the group statistical analyses, only two findings were of statistical significance: (a) the athletes that performed a gather versus a traditional approach technique jumped farther and (b) the flight time was longer for the athletes that performed the hitch-kick compared to the sail flight technique. The low number of statistically significant findings was expected due to the lower number of participants in any given subgroup. However, tendencies to perform similar techniques relative to the higher versus lower skilled athletes were apparent (see Tables 3-5).

Two factors, the approach technique performed and the manner in which the support leg is placed on the takeoff board, appeared to be related to maintaining as much horizontal velocity as possible during the last two strides of the approach and preparing to generate vertical velocity during the takeoff phase. For the approach technique

performed, the COM_B was dropped by the end of the penultimate stride and either maintained or dropped more by touchdown onto the takeoff board giving the athletes a greater amount of time over which to apply a vertical impulse and, as a result, generate more vertical velocity than if the COM_B had not been dropped prior to takeoff. Dropping the COM_B may have been achieved by either not fully extending off the back support leg (Tidow, 1990) or by placing the touchdown foot farther in front of the COM_B than the previous stride (Hay, 1993a; Lees et al., 1994). As a result, in either case, horizontal velocity is lost.

The approach technique performed was determined by the vertical displacement of the COM_B from touchdown of the penultimate stride to the touchdown of the last stride of the approach using the criterion of -0.03 m. Hay and Nohara (1990) reported that NonAmp athletes drop the COM_B 0.03-0.05 m during the penultimate stride. Similarly, for this study, the six men dropped the COM_B during the penultimate stride 0.02 m to 0.06 m and then dropped the COM_B 0.01 m to 0.07 m further by touchdown onto the takeoff board. The four women athletes maintained or raised the COM_B 0.00 m to 0.12 m. Furthermore, of these four athletes, only one (Participant 4) exhibited a total COM_B displacement of more than -0.02 m by touchdown onto the takeoff board.

Using the data from the three pentathlon athletes, it was determined that two athletes had a longer penultimate stride while one had a shorter penultimate stride than third-to-last stride. However, Hay, Miller, & Canterna (1987) reported that among elite NonAmp long jump athletes, the length of the third-to-last stride in relation to the length of the penultimate stride varies from athlete to athlete. When comparing the penultimate stride to the last stride length, five athletes had a longer last stride while five had a shorter last stride than penultimate stride. Of the five that had a shorter last stride than penultimate stride length only one also had a shorter third-to-last stride than penultimate stride length. The longer length of the penultimate stride than the last stride may be explained by the athletes having less extension off the back support leg (less knee flexion) at the instant of takeoff to the penultimate stride than the last stride.

Another strategy that could have been used by the athletes to drop their COM_B during the penultimate stride, was to land with more knee flexion at touchdown of the last stride (ProsL = support limb) than at touchdown of the penultimate stride (NProsL = support limb). It was expected that some of the TranTib athletes would have less knee flexion in the support phase of the ProsL than the NProsL, based on the study of TranTib running by Sanderson and Martin (1996). The athletes in this study may have felt more stable on their ProsL than the non-athletic participants of Sanderson and Martin's study.

It was also hypothesized that the athletes that performed the gather approach technique would: (a) have a greater decrease in horizontal takeoff velocity and a greater increase in vertical takeoff velocity and (b) jump farther compared to the athletes that performed the traditional approach technique. The amount of horizontal velocity maintained through the approach phase influences the horizontal takeoff velocity and ultimately the distance jumped. As expected, the athletes that performed the gather approach technique had a greater loss of horizontal takeoff velocity, but a greater increase in vertical takeoff velocity than the athletes that performed the traditional approach technique.

This finding, however, is confounded by the observation that the athletes that performed the gather approach technique were all men while the athletes that performed the traditional approach technique were all women plus the third place male (Participant 7). Therefore, the finding that the athletes that performed the gather approach technique jumped farther than the athletes that performed the traditional approach technique is gender biased. The women in this study were within the top five ranking TranTib long jump athletes in the world in 1998 (<http://www.topteam.de>), thus they are the most elite female TranTib long jump athletes. Therefore, it seems that at the time of this study, not dropping the COM_B during the penultimate stride was the best technique for these women athletes. Furthermore, it is not known if these athletes could have jumped farther if they had dropped the COM_B during the penultimate stride instead of during the last stride of the approach.

The second factor related to maintaining as much horizontal velocity as possible during the approach while preparing to generate vertical velocity during takeoff is the manner in which the takeoff foot is placed on the takeoff board. The active landing technique helps to maintain horizontal takeoff velocity and generate little vertical takeoff velocity (Koh & Hay, 1990) while the height technique diminishes horizontal takeoff velocity and generates more vertical takeoff velocity (Marino & Young, 1990; McLean, 1995). All but one athlete in this study used an active landing technique. These athletes spent less time on the takeoff board enabling them to tend to have a greater increase in horizontal and vertical velocities during the takeoff phase than the athlete that performed a height technique. This finding may be attributed to the skill level of the athlete performing the height technique (lowest skilled female).

For the flight phase of this study, the athletes that had a longer flight time (El Khadem & Huyck, 1966) were expected to perform the hitch-kick flight technique. The hitch-kick flight technique is more complicated than the hang or sail flight technique and therefore requires more flight time to perform.

For this study, four male athletes performed the hitch-kick while two male and three female athletes performed the sail flight technique. The athletes that performed the hitch-kick had a greater flight time than the athletes that performed the sail flight technique. However, Participant 10 used a hitch-kick although the flight time was the same or shorter than Participants 9 and 7, respectively, who performed the sail flight technique. This may indicate that Participants 9 and 7 should be performing the hitch-kick flight technique. The flight time findings, for this study, are in agreement with El Khadem and Huyck (1966) who surmised that the flight time constrained the flight technique performed. This could also mean that the flight time determines the flight technique performed. The athletes that performed the hitch-kick tended to jump farther than the athletes that performed the sail flight technique.

Part of the purpose of the flight technique is to get the body into position for landing. When landing, the athlete wants to hold the feet up as long as possible to

increase the distance of the jump. In addition, by landing with the feet in front of the COM_B , the jump distance is maximized. Therefore, the athlete wants a lower leg landing angle close to 5° . For this study, the athletes that performed the hitch-kick tended to have a smaller lower leg landing angle than the athletes that performed the sail flight technique. This could be due to the athletes that performed the hitch-kick having stronger abdominal and hip flexor muscles, being able to control their trunk position better than the athletes that performed the sail flight technique or to gender. The athletes with a smaller lower leg landing angle tended to land with the legs near parallel to the ground with the hips flexed, bringing the trunk close to the thighs. The athletes with a larger lower leg landing angle landed either standing almost straight up with very little hip flexion or with the legs near parallel to the ground with a small knee flexion angle.

It was expected that some of the athletes would fall to one side or the other upon landing. Of all the athletes, only two athletes fell to the NProsL side after landing. Upon landing, they both flexed the lower extremities, bringing the body towards the feet upon landing. This may have been due to the athletes trying to reduce the impact forces to the residual limb. All of the other athletes fell forward over their feet upon landing indicating that they did not hold their feet up as long as possible and as a consequence subtracted from the distance jumped.

In summary, in this study, the higher skilled athletes shared similar performance techniques. All the men dropped the COM_B while all the women raised the COM_B by the end of the penultimate stride. However, factors influencing the women's performances that vary from the men's performances are not known making it difficult to determine if dropping the COM_B is advantageous for the TranTib athletes. The men also lowered the COM_B while only one woman lowered the COM_B more than 0.02 m by touchdown onto the takeoff board. These actions caused the men to have a greater decrease in horizontal takeoff velocity while having a greater increase in vertical takeoff velocity than the women, including the one (lowest skilled woman) who lowered her COM_B more than 0.02 m by touchdown onto the takeoff board. All but one athlete, the lowest skilled

woman, performed an active landing technique. The flight technique performed, for this study, seems to be determined by flight time. A small lower leg landing angle is achieved by the athletes that have their legs near parallel to the ground with the hips flexed bring the trunk close to the thighs. Since the findings of this study were limited by the small number of participants, more research needs to be conducted with a larger number of participants to determine the performance techniques needed to perform a maximal length jump for TranTib athletes.

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CHAPTER IV

A KINEMATIC ANALYSIS OF TECHNIQUES USED BY ELITE AMPUTEE LONG
JUMP ATHLETES. PART II: TRANSFEMORAL CLASSIFICATION⁵

⁵ Ciapponi, T. M. and Simpson, K. J. to be submitted to Journal of Applied Biomechanics

ABSTRACT

The transfemoral (TranFem) amputee long jump athletes have limited biomechanical research conducted to determine performance techniques used by the athletes that jump the farthest. As such, the purpose of this study of elite TranFem athletes was to determine how the kinematic characteristics exhibited during long jump performances varied between higher and lower skilled long jump athletes

All of the long jump performances of the women's long jump ($n = 1$) and the men's long jump and pentathlon competitions ($n = 4$) were videotaped for analysis at the 1998 Ultimate Challenge Track and Field Invitational and 1999 National Summer Games, respectively. The farthest legal jump for each participant was selected for analysis. Due to the small sample sizes, non-parametric statistics (Kolmogorov-Smirnov, Mann-Whitney U, and chi-square tests) were used to analyze technique based hypotheses ($p < 0.05$).

The top two TranFem male athletes exhibited conflicting performance techniques, making it difficult to determine the optimal performance techniques. However, the following performance techniques were used by the higher skilled athletes:

1. Dropped the COM_B during the penultimate stride of the approach and then lowered it further until touchdown onto the takeoff board or lowered it only during the last stride.
2. Placed the takeoff foot onto the takeoff board in a backward sweeping motion.
3. Performed the sail flight technique.
4. Achieved a small lower leg landing angle by the athletes having their legs extended about the knee joints and flexing the trunk about the lower vertebral joints causing a reaction of hip flexion.

Introduction

The research on long jump performance techniques used by athletes with a unilateral transfemoral (TranFem) amputation is very limited. The stride kinematics of three TranFem athletes for the approach phase (Simpson, Williams, Ciapponi, Wen, & Del Rey, 2000; Simpson, Williams, Ciapponi, Wen, Nance, & Valleala, 1998) and the takeoff mechanics for eight athletes (Nolan & Lees, 1999) are the only known biomechanic topics investigated to determine how performance effectiveness is achieved by elite TranFem long jump athletes. Furthermore, a comprehensive understanding of the biomechanics of elite TranFem performance is complicated by the high interparticipant variability apparent in these studies that could be attributed to the various levels of amputation, prostheses worn, amounts of training, etc.

TranFem long jump athletes use a sport prosthesis design that varies from transtibial (TranTib) amputee long jump athletes' in that the prosthesis has a prosthetic knee. The prosthetic knee joint functions to allow the participant to have smooth and controlled lower leg and foot movement during the swing phase of walking or running and to have stability during weight bearing. Most athletes use a hydraulic knee component that has a cylinder filled with synthetic oil to provide swing phase control (May, 1996). Some knee motion control is possible, however, as the athlete can adjust the magnitude of the normal frictional component and the range of motion of the knee, even with swing phase control. However, the point in time in which the knee extends cannot be controlled.

Thus when using a TranFem prosthetic design, the constraints on lower extremity motor control and coordination and muscular force absorption and generation are even greater for TranFem athletes than TranTib athletes. Body segment mechanical differences, e.g., reduced knee flexion range of motion, and lower extremity muscle moment differences exist between the prosthetic limb (ProsL) and non-prosthetic limb (NProsL) because compensatory actions occur in response to the use of a prosthesis that has different mechanical properties than an intact limb, e.g., force generating properties

and inertial characteristics; and due to the changes in the residual limb, e.g., loss of musculature and neuromuscular control (Brouwer, Allard, & Labelle, 1989; Buckley, 1999; Ehara, Beppu, Nomura, Kunimi, & Takahashi, 1993; Sanderson & Martin, 1996; Simpson et al., 1998; Simpson et al., 2000).

Therefore, whether TranFem athletes should use the same movement techniques as elite NonAmp athletes in order to make similar use of mechanical principles during locomotor activities is controversial. As the prosthetic constraints may influence the mechanics of the long jump during its various phases, the long jump is an ideal movement for investigating how TranFem athletes adapt to the morphological and environmental constraints related to the residual limb and prosthesis, respectively. Therefore, to generate a more comprehensive understanding of optimal performance techniques used by TranFem long jump athletes, the purpose of this study was to determine how the kinematic characteristics exhibited during long jump performances varied between higher and lower skilled athletes.

As described in Part I (Ciapponi & Simpson, submitted) the effectiveness of several movement techniques were investigated. To position the body at a low height for the takeoff phase, NonAmp and TranTib athletes have been reported to use either the traditional or gather approach technique. Whereas the height of the body's center of mass (COM_B) remains the same during the penultimate stride for the traditional approach technique, for the gather approach technique the COM_B is dropped during the penultimate stride of the approach. Then the COM_B height either remains relatively constant or continues to be lowered until touchdown onto the takeoff board (Hay, 1993a; Hay & Nohara, 1990; Koh & Hay, 1990; Lees, Fowler, & Derby, 1993; Luhtanen & Komi, 1979; Tidow, 1990; Weidner & Dickwach, 1990). The advantage to using the gather approach technique is that by dropping the COM_B during the penultimate stride and maintaining this height, the athlete will not have to lower the body during the takeoff phase, but instead, can utilize the vertical ground reaction impulse to generate only upward momentum (Hay & Nohara, 1990).

However, it is not known if the TranFem athletes would lower the COM_B during the penultimate stride of the approach. Based on amputee long jump literature, the height of the COM_B at touchdown onto the takeoff board was found to be higher for TranTib and NonAmp athletes than TranFem athletes and the COM_B was observed to displace downwards after contact onto the takeoff board (Nolan & Lees, 1999). These findings were surmised to be due to the lack of a fully functional knee. In addition, an anticipated lack of ProsL versus NProsL knee flexion was expected to affect the approach technique used by TranFem athletes.

One method of achieving a lower COM_B during the penultimate stride of the approach is the ability to have more knee flexion during the support phase of the last stride than the previous stride. Buckley (1999), Ciapponi, Simpson, Wang, McKee, and McAllister (1999), Simpson et al. (1998), and Wang, Simpson, Ciapponi, McKee, and McAllister (1999) reported less knee flexion for the ProsL compared to the NProsL during the support phase of running for the TranFem. Therefore, it is expected that only those athletes who jumped the farthest (most highly skilled) would drop the COM_B 0.03 m or more during the penultimate stride of the approach (Hay & Nohara, 1990).

Another technique used to drop the COM_B during the penultimate stride is to place the touchdown foot in front of the COM_B at a farther distance than the previous stride and last stride of the approach (Hay, 1993a; Lees, Graham-Smith, and Fowler, 1994). As reported by Simpson et al. (1998), TranFem long jump athletes exhibited a longer penultimate stride than the previous and last strides of the approach. However, as the TranFem athletes all pushed off the NProsL at the start of the penultimate stride, a longer penultimate stride than the previous and last strides was expected. Therefore, to determine if the TranFem athletes in this study had a longer penultimate stride than the previous and last strides, the penultimate stride length also had to be longer than the previous NProsL stride (fourth-to-last stride).

Another movement technique investigated that influences horizontal and vertical takeoff velocities is the manner in which the takeoff foot is placed on the takeoff board.

The takeoff board landing technique may serve to either minimize the loss of horizontal velocity during takeoff by minimizing the braking forces applied during the takeoff phase (active landing technique) or serve to augment vertical takeoff velocity by increasing the time in which upward vertical momentum can be generated for takeoff (height technique) (Marino & Young, 1990; McLean, 1995). For a full description of the active landing and height techniques see Part I. When performing the active landing versus the height technique the takeoff foot is planted near the anteroposterior position of the COM_B in a backwards pawing action versus placing the foot far in front of the COM_B. This action causes the athlete's COM_B to quickly pass over the takeoff foot, resulting in a small amount of time to generate vertical impulse during takeoff (Marino & Young, 1990; McLean, 1995).

It was expected that for this study, the higher skilled TranFem athletes would perform an active landing technique to take advantage of maintaining horizontal velocity and because the NProsL is the limb that performs the action of the active landing technique. It was predicted that those athletes that performed an active landing technique would also be on the takeoff board for a shorter duration of time and have a greater increase in horizontal takeoff velocity and a greater decrease in vertical takeoff velocity than the athletes that performed a height technique.

El Khadem and Huyck (1966) surmised that the flight technique performed depends on the amount of time spent in the air. The hitch-kick flight technique takes longer to perform than the hang or sail flight techniques so the athlete must be in the air long enough to perform the hitch-kick flight technique. It was not known if TranFem long jump athletes would perform a particular flight technique suitable to the athlete's flight time. However, it was expected that, for this study, the athletes would not be in the air long enough to perform the hitch-kick flight technique but, instead, would perform either the hang or sail flight technique.

An athlete wants to keep the legs and feet in the air as long as possible to maximize distance while simultaneously moving the body into an optimal position for

landing effectively and safely. Therefore, to accomplish this, the athlete will land with the legs near parallel to the ground with the knee joints slightly flexed and the hip joints flexed, while flexing the trunk toward the thighs (Hay, 1993a) (see Figure 6 in Part I). Thus far, the only study to report any information on the techniques used during the landing phase for TranFem athletes is an unpublished technical report (Simpson, Williams, Ciapponi, Wen, & Nance, 1997). The authors reported that all of the TranFem long jump athletes tended to fall laterally toward one side or the other upon landing. They postulated that the athletes were attempting to reduce the impact forces to the residual limb. They also surmised that because the ProsL length is longer compared to the NProsL that, at contact, the ProsL would contact the ground first, creating a torque in the frontal plane that would cause the body to rotate, i.e., to fall toward the NProsL side. Therefore, for this study, it was hypothesized that falling to one side or the other was an indicator that the feet contacted the ground too soon which reduced the distance of the jump.

Methodology

As in Part I (Ciapponi & Simpson, submitted), all of the long jump performances of the TranFem long jump and pentathlon competitions were videotaped for analysis at the 1998 Ultimate challenge Track and Field Invitational and at the 1999 National Summer Games, respectively. Table 6 depicts performance data for all participants (females: $n = 1$ and males: $n = 4$). For a complete description of the specifications related to the cameras, their locations for a given data collection configuration, the calibration marker length, and the movements captured by each camera, see Table 2 in Part I (Ciapponi & Simpson, submitted).

The farthest legal jump for each participant was selected for analysis. The Peak Motus32 Motion Measurement™ system (v. 4.3.3) was used to digitize an 18-point model of the body, including the prosthesis (see Figure 13). The raw data were then smoothed using a quintic spline (Jackson, 1979). Velocities were calculated using a forward-difference algorithm for the first point, a second-order central difference algorithm for the

Table 6

Competition, Distance Jumped and CompetitionResults for All Participants

| Event and Participant no. | Competition | Distance Jumped (m) | Place in Event |
|------------------------------|-----------------------|------------------------|-------------------|
| Women's | Ultimate Challenge | | |
| 11 | | 2.79* | 1 |
| Men's | U.S. Nationals | | |
| 12 | | 4.90 | 1 |
| 13 | | 4.90 | 2 |
| Men's Pentathlon | U.S. Nationals | | |
| 14 | | 4.33 | 1 |
| 15 | | 2.95 | 2 |

Note. *World record.

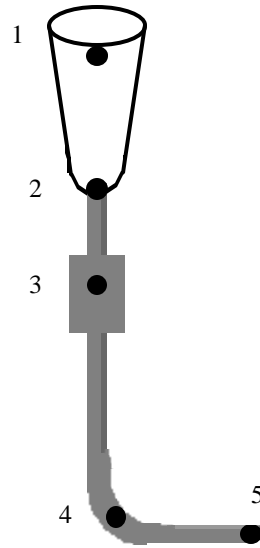


Figure 13. The points digitized for the prosthesis: (1) top of socket, (2) bottom of socket, (3) knee, (4) ankle, and (5) toe.

second point, and a backward-difference algorithm for the remaining points (Peak Performance Technologies™, 1998).

Anthropometric Measurements

To generate the COM_B coordinates the COM of all of the body's segments except the residual limb and the prosthesis were generated using the gender specific regression equations of Plagenhoef (1983). The computation of the COM of an athlete's prosthesis (see Appendix E⁶) and residual limb are explained in Part I (Ciapponi & Simpson, submitted).

Quantities Generated

The quantities generated for the TranFem athletes in this study were identical to those generated in Part I (Ciapponi & Simpson, submitted). The quantities were: (a) the COM_B height at the instant of touchdown of the penultimate and last strides of the approach, (b) the length of the last four strides and last two strides of the approach for the pentathlon and all athletes, respectively, (c) the horizontal velocity of the takeoff foot's COM relative to the COM_B just prior to touchdown onto the takeoff board, (d) lower leg landing angle (see Figure 9 in Part I), (e) time on the takeoff board, and (f) flight time.

Data Analysis

Due to the small sample size, non-parametric statistics were used to analyze the data (Siegel & Castellan, 1988). SPSS (v. 9) was used to calculate the statistics. To determine if TranFem athletes lowered their COM_B from the penultimate stride to the last stride and/or performed a penultimate stride length longer than the third-to-last and last strides of the approach a Kolmogorov-Smirnov (KS) test was used. To compare the values of variables between the gather versus the traditional approach technique subgroups, and similarly to compare the variables of the landing technique subgroups and the flight technique subgroups, a Mann-Whitney U test was used. A chi-square test was used to determine if there were differences among flight techniques for the frequency of

⁶ Appendix E is at the end of the dissertation.

athletes that used a given flight technique. All statistical procedures were considered significant if $p < 0.05$.

Results

No statistically significant differences were found for any of the variables. This was expected due to the low number of participants in any given sub-group. Also, high variability among the performances of TranFem athletes has been reported (Nolan & Lees, 1999; Simpson et al., 1998; Simpson et al., 2000). As such, the individual participant data are of more interest than the statistical results.

The results are presented in order of the long jump phases: approach, takeoff, flight, and landing. The vertical displacement of the COM_B of the penultimate stride was used to determine if the athletes dropped the COM_B 0.03 m or more by the end of the penultimate stride. Values ranged from -0.05 m to 0.10 m, demonstrating the variability among participants. Two athletes raised the COM_B (positive displacement) while three dropped the COM_B (negative displacement) (see Figures 14a-b). The three athletes that dropped the COM_B were categorized as performing the gather approach technique while the remaining two athletes were categorized as performing the traditional approach technique. The athletes that performed the gather approach technique continued to drop the COM_B , 0.05 m to 0.08 m, while the athletes that performed the traditional approach technique dropped the COM_B 0.06 m to 0.07 m, by touchdown onto the takeoff board.

One technique used to lower the height of the COM_B is by having a penultimate stride length longer than the preceding stride and last stride of the approach. For the men's pentathlon ($n = 2$), there were no significant differences found for the running cycle lengths or the relative contributions to the respective running cycles of the third-to-last stride and the penultimate stride. Both athletes tended to have a longer penultimate stride compared to the third-to-last stride of the approach (see Figures 15a-b). This suggests that a longer penultimate stride was used as one method to lower the COM_B during the penultimate stride of the approach.

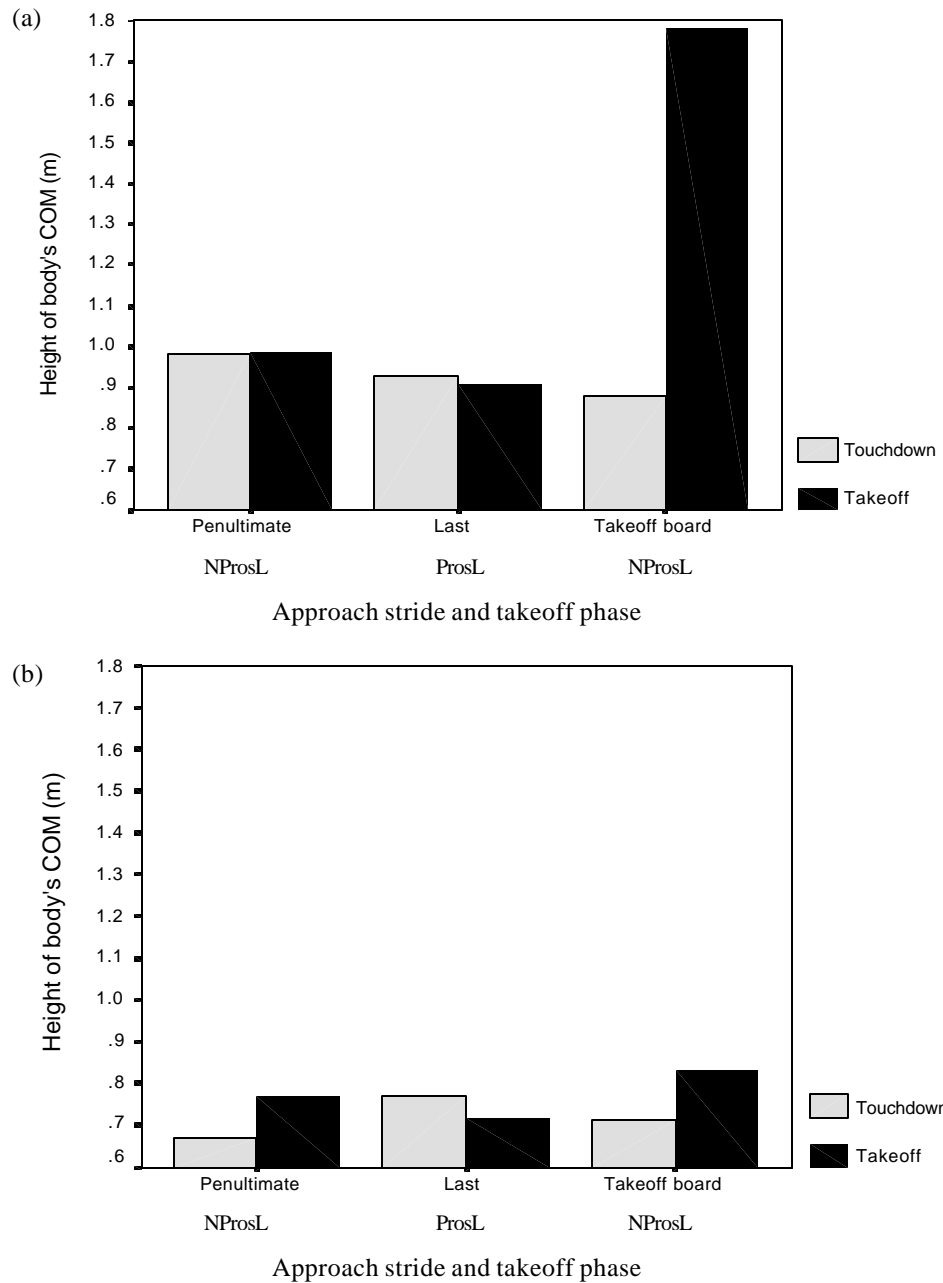


Figure 14. Body's COM height at touchdown and takeoff of the support phases of the last two strides and the takeoff phase. Representative participants that exhibited vertical displacement of the penultimate stride that was: (a) negative (Participant 14) and (b) positive (Participant 11). The support phase limb is identified as the non-prosthetic (NProSL) or prosthetic (ProSL) limb.

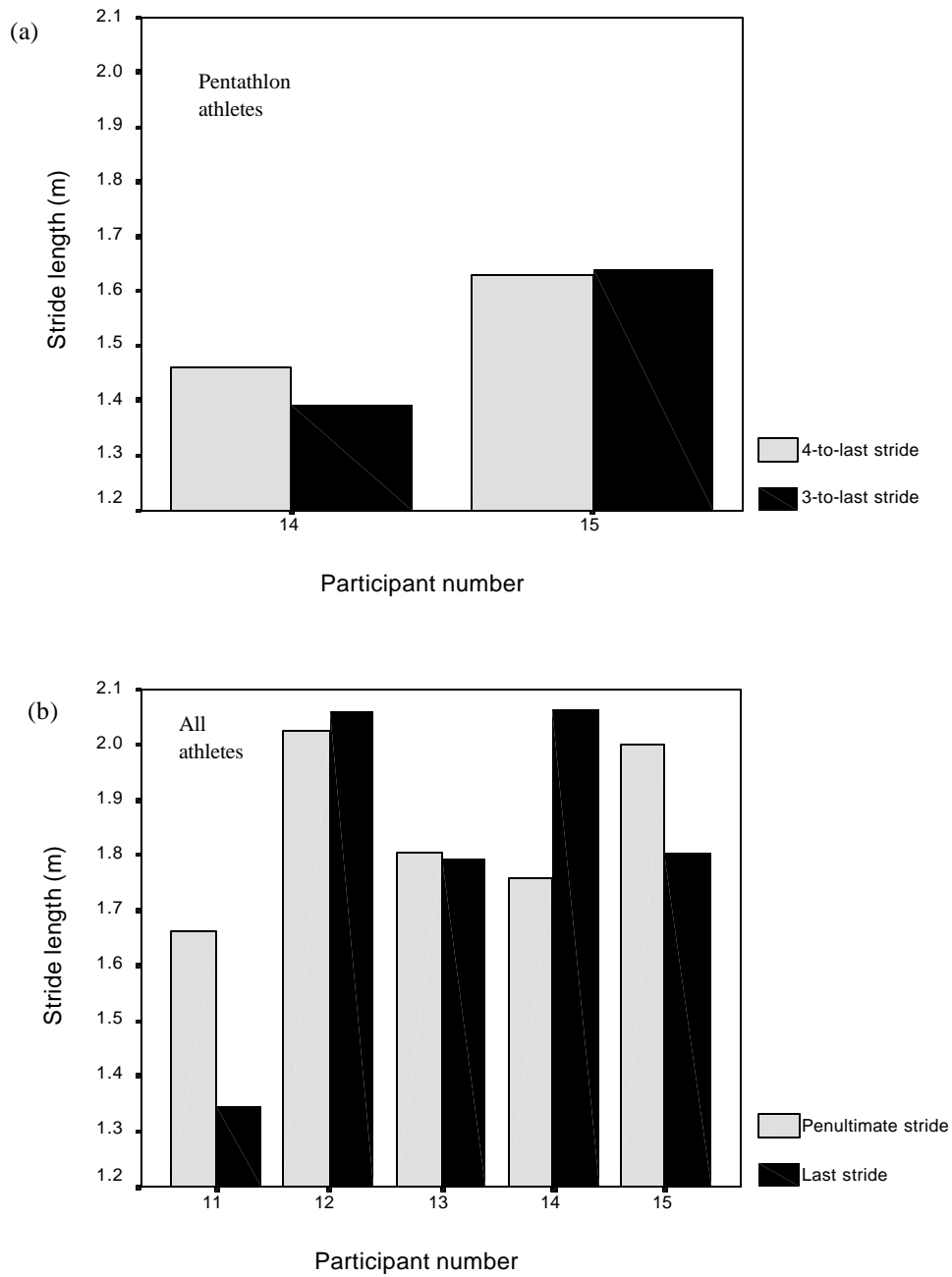


Figure 15. (a) The stride lengths for the first running cycle of the 2 men's pentathlon athletes and (b) the stride lengths for the second running cycle for each participant.

When comparing the length of the penultimate stride to the last stride of the approach, no significant difference was found. Stride length differences (penultimate – last) ranged from –0.40 m to 0.32 m with three athletes tending to have a longer penultimate stride while two athletes tended to have a shorter penultimate stride than the last stride (see Figure 15b). The three athletes that had a longer penultimate stride also may have used this method to lower the COM_B during the penultimate stride of the approach.

Another technique used to lower the height of the COM_B is by not fully extending off the back support leg at takeoff of the penultimate stride (Tidow, 1990). The athletes that performed the gather approach technique tended to have more support knee flexion at takeoff of the penultimate stride than the athletes that performed the traditional approach technique (see Table 7). This suggests that not fully extending off the back support leg of the penultimate stride was used as one method to lower the COM_B during the penultimate stride of the approach.

As shown in Figure 16a-b and Table 7, the athletes that performed the gather approach technique tended to lose more horizontal velocity, with losses ranging from 0.87 m/s to 1.88 m/s, and gained more vertical velocity (increases in velocity = 2.18-3.28 m/s) during the takeoff phase than the athletes that performed the traditional approach technique. The athletes that performed the traditional approach technique had a loss of horizontal velocity ranging from 0.32 m/s to 0.79 m/s and a gain of vertical velocity (1.63-3.08 m/s) during the takeoff phase.

It was hypothesized that having negative horizontal velocity of the takeoff foot relative to the COM_B ($v_{rel\ ft}$) just prior to touchdown onto the takeoff board (active landing technique) would result in less time on the takeoff board and less of a decrease in horizontal velocity and less of an increase in vertical velocity during the takeoff phase compared to performing the height technique. All five of the athletes had a negative relative horizontal velocity of the takeoff foot in relation to the COM_B . Therefore, all the athletes were categorized as performing an active landing technique (see Table 8).

Table 7

Individual Participant Values for Approach and Takeoff Phases

| Variable | Participants | | | | |
|--|--------------|-----------|-------------------|-------|-------|
| | Woman | Men | | | |
| | <u>LJ</u> | <u>LJ</u> | <u>Pentathlon</u> | | |
| | 11 | 12 | 13 | 14 | 15 |
| Gather approach technique (Y/N) | N | N | Y | Y | Y |
| Distance jumped (m) | 2.79 | 4.90 | 4.90 | 4.33 | 2.95 |
| Knee angles at (°) : | | | | | |
| Touchdown of penultimate stride | 159 | 171 | 158 | 163 | 151 |
| Takeoff of penultimate stride | 170 | 150 | 136 | 134 | 152 |
| Touchdown of last stride | 165 | 169 | 171 | 153 | 174 |
| Takeoff of last stride | 160 | 175 | 168 | 162 | 164 |
| Touchdown onto the takeoff board: | | | | | |
| Change in velocity _{takeoff phase} = $V_{\text{end}} - V_{\text{start}}$ (m/s) | | | | | |
| Change in V_x | -0.32 | -0.79 | -1.88 | -1.26 | -0.87 |
| Change in V_y | 1.63 | 3.08 | 3.28 | 2.18 | 2.74 |

Note. LJ = long jump. Gather approach technique = “Y” when the body’s COM vertical displacement is -0.03 m or greater during the penultimate stride of the approach.

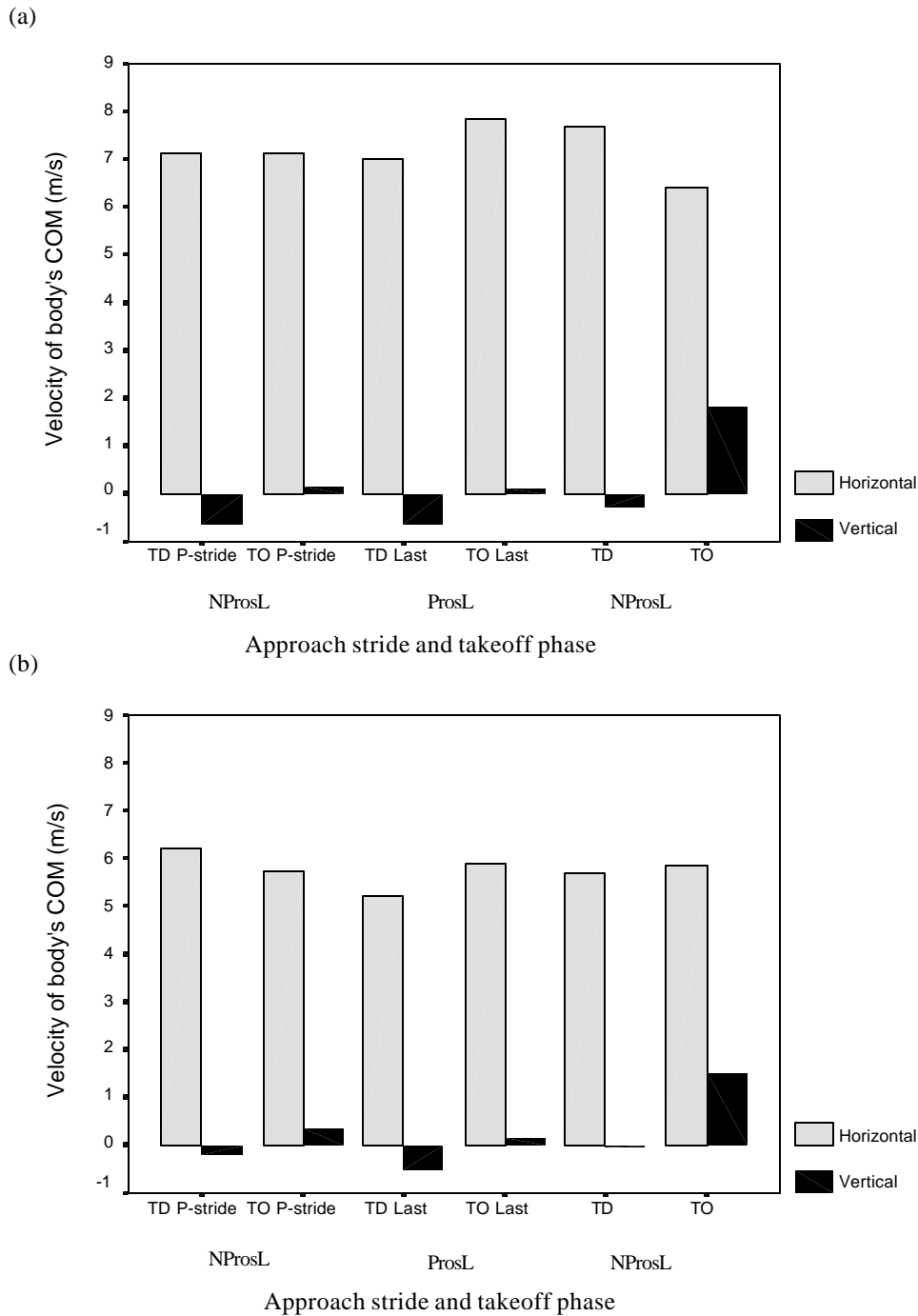


Figure 16. Horizontal and vertical velocities of body's COM at touchdown (TD) and takeoff (TO) for the penultimate (P-stride) and last stride of the approach and the takeoff phase. The graphs depict representative participants that exhibited; (a) a gather (Participant 14) and (b) a traditional (Participant 11) approach technique. The support phase limb is identified as the non-prosthetic (NProSL) or prosthetic (ProSL) limb.

Table 8

Individual Participant Values for Athletes Performing the Active Landing Technique (n = 5)

| Variable | Participants | | | | |
|---|--------------|-----------|-------------------|-------|-------|
| | Woman | Men | | | |
| | <u>LJ</u> | <u>LJ</u> | <u>Pentathlon</u> | | |
| | 11 | 12 | 13 | 14 | 15 |
| V_x of takeoff foot relative to V_x of body's COM (m/s) | -2.32 | -1.84 | -1.69 | -3.43 | -1.00 |
| Time on takeoff board (s) | 0.15 | 0.15 | 0.13 | 0.19 | 0.17 |
| Takeoff variables: | | | | | |
| V_x of body's COM (m/s) | 5.37 | 7.26 | 6.44 | 6.42 | 5.08 |
| V_y of body's COM (m/s) | 1.57 | 2.28 | 2.34 | 1.89 | 1.81 |

Note. LJ = long jump.

For the flight variables, one athlete (Participant 13) performed the hitch-kick while four athletes performed the sail flight technique (see Table 9). Participant 13 tended to have a greater flight time than the athletes that performed the sail flight technique. However, Participant 13 had the third lowest lower leg landing angle with Participants 12 and 14 having the lowest two lower leg landing angles. The athlete that performed the hitch-kick flight technique tended to jump farther than the athletes that performed the sail flight technique. Only the participant that performed the hitch-kick fell to the ProsL side after collapsing towards the feet upon landing.

Discussion

To understand the kinematic characteristics used by TranFem athletes and to distinguish the performance characteristics between the higher skilled (jumped farther) and lower skilled athletes, three questions were asked: (a) what movement techniques were used to create optimal vertical and near maximal takeoff velocities during the approach and takeoff phases; (b) are the flight phase movements appropriate for positioning the body for an optimal landing, given the flight time; and (c) what movement techniques are exhibited during the landing phase that allow the athlete to maximize the landing distance?

Although no statistically significant differences were found, some tendencies to perform similar performance techniques among the athletes that jumped the farthest were apparent (see Tables 7-9).

The gather approach technique is distinguished from the traditional approach technique by dropping the COM_B 0.03 m or more during the penultimate stride of the approach (Hay & Nohara, 1990). Participants 13, 14, and 15 (the second through fourth place athletes) dropped the COM_B during the penultimate stride of the approach. Participants 11 and 12 (the first place woman and man, respectively) raised the COM_B during the penultimate stride. Of the three athletes that dropped their COM_B , only one, Participant 14, had more knee flexion at touchdown of the last stride than at touchdown of the penultimate stride. This suggests that this athlete may have used a method

Table 9

Individual Participant Values for Athletes Performing the Hitch-Kick
(n = 1) and Sail (n = 4) Flight Techniques and Landing Position

| Variable | Participants | | | | |
|--------------------------------|--------------|------|-----------|-------------------|------|
| | Woman | | Men | | |
| | <u>LJ</u> | | <u>LJ</u> | <u>Pentathlon</u> | |
| | 11 | 12 | 13 | 14 | 15 |
| Flight technique | S | S | HK | S | S |
| Flight time (s) | 0.40 | 0.63 | 0.63 | 0.53 | 0.52 |
| Lower leg landing angle (°) | 65 | 41 | 49 | 46 | 62 |
| Fell to one side (Y/N) | N | N | Y | N | N |

Note. LJ = long jump. S = sail flight technique. HK = hitch-kick flight technique.

requiring more knee flexion at touchdown of the last stride than the penultimate stride to lower the COM_B during the penultimate stride. Buckley (1999) reported less knee flexion occurred during the support phase of the ProsL compared to the NProsL, and he surmised that this was perhaps due to ProsL being used as a rigid support. However, Buckley's single TranFem participant wore a walking prosthesis, while for this study, Participant 14 wore a sports prosthesis. The sports prosthesis may have been able to provide more support at the knee upon contact with the ground than the walking prosthesis, enabling him to feel stable enough to drop the COM_B during the penultimate stride of the approach. However, all three athletes had a less extended knee angle at takeoff to the penultimate stride than the last stride. This finding is consistent with the findings of Tidow (1990), who noted that NonAmp athletes have been found to drop the COM_B by extending off the support leg less at takeoff of the penultimate support phase than the last support phase.

Another technique used to drop the COM_B in the gather approach technique is by having a longer penultimate stride length than the lengths of the preceding and last strides of the approach (Hay, 1993a; Lees et al., 1994). For the two athletes (the pentathletes) for which there were data available, it was determined that they both had a penultimate stride length longer than the third-to-last stride length. This technique may partially explain how the COM_B was lowered during the penultimate stride of the approach.

For the length of the penultimate stride in comparison to the last stride, three of the five athletes (Participants 11, 13, and 15) had a longer penultimate stride than last stride. These athletes performed this technique which may have allowed them to drop the COM_B during the penultimate stride of the approach. However, even though Participant 11 had a longer penultimate stride than the last stride, she had a larger knee angle at touchdown of the last stride than at touchdown of the penultimate stride. This phenomenon may have negated her chance of lowering the COM_B during the penultimate stride of the approach.

In this study, the male athletes that dropped the COM_B (Participants 13, 14, and 15) tended to jump farther than the athletes that raised the COM_B during the penultimate stride. For Participant 11 (the only female athlete), the COM_B was lowered 0.07 m during the last stride of the approach. Perhaps the COM_B was not lowered during the penultimate stride (support limb = NProsL) to avoid having to land onto the ProsL in a flexed knee position for the last stride.

The amount of horizontal and vertical velocities generated during takeoff influence the distance jumped. Therefore, the influence of approach technique actions on the change in horizontal and vertical velocities are of interest. When comparing the gather to the traditional approach technique, NonAmp athletes have been reported to have a greater decrease in horizontal takeoff velocity and a greater increase in vertical takeoff velocity (Ciapponi, 1996). As expected, the athletes for this study that performed the gather approach technique tended to have a greater decrease in horizontal takeoff velocity and generate more vertical takeoff velocity than the athletes that performed the traditional approach technique.

The manner in which the takeoff foot is placed on the takeoff board also influences the generation and/or loss of horizontal and vertical velocities during takeoff. NonAmp athletes who exhibit an active landing technique maintain more horizontal takeoff velocity while generating less vertical takeoff velocity than those athletes performing a height technique (Young & Marino, 1984). All of the athletes in this study performed an active landing technique. Even though Participants 12 and 13 (the top two male athletes) spent less time on the takeoff board, they generated more horizontal and vertical takeoff velocities than the other athletes. As a result, Participants 12 and 13 jumped farther than the other athletes.

For the flight phase of this study, based on the available flight time, it was expected that the TranFem athletes would perform the hang or sail flight technique. While all but one athlete performed the sail technique, this prediction was confirmed. Unexpectedly, one of the top two male athletes (Participant 13) performed the hitch-kick

flight technique. It may be that Participant 12 should be performing the hitch-kick flight technique instead of the sail flight technique.

Part of the purpose of the flight technique is to get the body into position for landing. Second, prior to landing, the athlete wants to hold the feet up as long as possible to increase the distance of the jump. Thus a lower leg landing angle of approximately 5° indicates if an athlete achieved these goals. For this study, among the male participants, the athletes that jumped the farthest (Participants 12-14) had smaller lower leg landing angles ($41\text{-}49^\circ$) than and Participant 15, the lowest skilled male participant (62°). Participant 11, the only women (65°) also had one of the highest lower leg landing angles. This indicates that these participants did not hold their feet up as long as possible and as a consequence reduced the distance of their jumps. Participants 12-14 may have had stronger abdominal and hip flexor muscles or may have been able to control their trunk position better than the other participants.

Upon landing, only Participant 13 fell to the NProsL side after flexing his lower extremities bringing his body toward his feet. This could have been due to the lack of active control over the prosthetic knee and prosthetic knee settings restricting knee flexion angular velocity. Participants 11 and 15, who had greater lower leg landing angles than the other participants, landed standing almost straight up. Even though Participant 12 had one of the farthest jumps, he could have jumped farther. He failed to flex his lower extremities bringing his body toward his feet upon landing and, as a result, landed on his gluteal region behind the initial point of contact of his feet in the landing pit.

As previously stated, little is known about the long jump mechanics performed by TranFem athletes (Nolan & Lees, 1999; Simpson et al., 1998; Simpson et al., 2000). In this study, the top two male athletes exhibited some performance techniques that may have compromised the distance of the jump for reasons that are not likely related to ProsL constraints. One dropped the COM_B during the penultimate stride, performed the hitch-kick flight technique, and flexed his lower extremities bringing his body toward his

feet, as expected, but he fell to one side upon landing. The other top male did not exhibit desired performance characteristics: he raised the COM_B during the penultimate stride, performed the sail flight technique, and did not flex his lower extremities during landing, causing his body to fall backwards subtracting from the distance of his jump. The only optimal performance techniques that these two athletes shared were the use of an active landing technique and the prevention of landing too early as both exhibited similar lower leg landing angles. The only woman in this study broke the women's world record with the jump analyzed in this study. The following performance techniques were demonstrated by her: (a) COM_B lowered during the last stride rather than the penultimate stride, (b) an active landing technique, (c) the sail flight technique, and (d) a high lower leg landing angle, reflecting no movement actions were used to maximize flight time or the body position for an effective landing.

Overall, TranFem athletes exhibited few adaptations to adjust for ProsL constraints relative to optimal elite NonAmp techniques. TranFem athletes who did exhibit adaptations appeared to be compensating primarily for the ProsL's lack of support phase knee flexion during the approach phase. Thus, lowering the COM_B during the last two strides of the approach was accomplished by less knee extension at takeoff of these strides and greater knee flexion at touchdown onto the takeoff board by the NProsL. Certainly, more research needs to be done before a pattern of performance techniques is identified as the best to improve performance for TranFem athletes.

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CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The previous biomechanical long jump research has been limited for lower extremity amputee athletes (Nolan & Lees, 1999; Simpson et al., 1998; Williams et al., 1997). As each phase of the long jump plays an integral role in the production of a maximal length jump, the kinematics of skilled long jump athletes for all four phases of the long jump were examined in this study. Therefore, a better understanding of the underlying biomechanical principles of long jump performance techniques specific to long jump athletes with lower extremity amputations will provide scientific evidence to guide these athletes as they continue to achieve improved performances.

Overall, for the TranTib athletes, only hypotheses 2b, the TranTib athletes that performed a gather approach technique will jump farther than the athletes that performed a traditional approach technique. and 5, the rank order (sail, hang, and hitch-kick) of the flight techniques performed by the TranTib amputee long jump athletes will be directly related to the flight time, were accepted. For the TranFem athletes, no hypotheses were accepted. With high variability among the performances of TranTib and TranFem athletes being reported, (Nolan & Lees, 1999; Simpson et al., 1998; Simpson et al., 2000) the individual participant data were of more interest than the statistical results.

For the TranTib athletes, to use the available takeoff phase time to generate vertical momentum, the men lowered while the women raised the COM_B during the penultimate stride of the approach. It is not known if dropping the COM_B during the penultimate stride is advantageous for all TranTib athletes. It may be that dropping the COM_B during the penultimate stride augments the jump distance for the men, but not for the women. The women in this study were four of the top five TranTib long jump athletes

in the world at the time they were videotaped. It appears that at this time, women TranTib athletes may jump farther by dropping the COM_B during the last stride of the approach. In regards to other factors, it may be said that the TranTib athletes who jumped the farthest (i.e., higher skilled) performed the following techniques:

1. Active landing technique onto the takeoff board: placed the takeoff foot onto the takeoff board in a backward sweeping motion, minimizing the decrease in horizontal velocity, but also minimizing the increase in vertical velocity during the takeoff phase.
2. Flight technique: the higher skilled athletes had a greater flight time due to higher vertical takeoff velocity, enabling them to perform the hitch-kick flight technique.
3. Body position prior to landing: in general, a small lower leg landing angle was achieved by the higher skilled athletes who demonstrated a position of legs near parallel to the ground with the hips flexed, with the trunk close to the thighs. This position was produced by trunk flexion (action) and hip flexion (reaction).

For TranFem athletes, the top two male athletes exhibited a combination of optimal and less-than-optimal techniques. One lowered the COM_B during the penultimate stride, performed the hitch-kick flight technique, and flexed his lower extremities bringing his body toward his feet, but fell to one side upon landing. The other top male athlete raised the COM_B during the penultimate stride, performed the sail flight technique, but did not flex his lower extremities bringing upon landing, causing him to fall backwards. The female TranFem athlete, who broke the world record with the jump analyzed in this study, raised the COM_B during the penultimate stride, but lowered it during the last stride, performed the sail flight technique, and landed with a high landing angle. The only performance technique that these three athletes shared was the use of an active landing technique. Therefore, although there were exceptions, in general, the following performance techniques were used by the higher skilled TranFem athletes:

1. Approach technique: COM_B was lowered during the penultimate stride of the approach and then lowered further until touchdown onto the takeoff board or

lowered only during the last stride. This action may have enabled the athletes to have a greater amount of time over which to generate positive vertical momentum during the takeoff phase although a greater decrease in horizontal velocity also occurred.

2. Active landing technique onto the takeoff board: placed the takeoff foot onto the takeoff board in a backward sweeping motion, minimizing the decrease in horizontal velocity, but also minimizing the increase in vertical velocity during the takeoff phase.
3. Flight technique: these athletes had a long enough flight time to enable all but one of them to perform the sail flight technique. The hitch-kick technique could be used by a TranFem athlete who has a flight time of at least 0.63 s.
4. Body position prior to landing: in general, a small lower leg landing angle was achieved by the higher skilled athletes who demonstrated a position of legs near parallel to the ground with the hips flexed, with the trunk close to the thighs. This position was produced by trunk flexion (action) and hip flexion (reaction).

Conclusions

Some gender differences were observed for the pattern of COM_B height during the last two strides of the approach, but the underlying reasons for these differences are not known, nor can it be determined how varying patterns may be advantageous to performance. Additional research needs to be conducted to further determine the biomechanics underlying the optimal performance techniques needed to produce a maximal length jump for TranTib and TranFem athletes.

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APPENDIX A

Checklist for Sail Flight Technique

- _____ 1. From takeoff position, brought both legs together in front of body.
- _____ 2. Knees were fully extended or slightly bent.
- _____ 3. Arms were extended out over the legs.
- _____ 4. Athlete was flexed at the hips (reaching for toes).
- _____ 5. In a distinct sitting position.

APPENDIX B

Checklist for Hang Flight Technique

- _____ 1. From takeoff position, the lead leg was brought back to join the takeoff leg behind the trunk.
- _____ 2. Both hips were hyperextended with the knees slightly bent..
- _____ 3. Both shoulders were hyperextended.
- _____ 4. Back was slightly arched (reverse 'C' position).
- _____ 5. Arms and legs brought forward together.
- _____ 6. Arms were extended out over the legs.
- _____ 7. Athlete was flexed at the hips (reaching for toes).

APPENDIX C

Checklist for Hitch-Kick Flight Technique

- _____ 1. From takeoff position, the lead leg was brought down and back as the takeoff leg was brought up and forward (in cyclic fashion).
- _____ 2. The lead arm was brought down and back as the trail arm was brought up and forward (in cyclic fashion).
- _____ 3. Steps 1 and 2 repeated (only for 2 ½ hitch-kick).
- _____ 4. Back leg and arm were brought forward to join front arm and leg.
- _____ 5. Arms and legs brought forward together.
- _____ 6. Arms were extended out over the legs.
- _____ 7. Athlete was flexed at the hips (reaching for toes).

APPENDIX D

Equations for Calculating Prosthesis Center of Mass for Transtibial Athletes

To obtain the necessary measurements for calculating the COM of the components of the prosthesis, four digitized points for TranTib athletes in the XY plane of the prosthesis were used: top of the socket (coordinates = TOS_x , TOS_y), bottom of the socket (coordinates = BOS_x , BOS_y), the ankle (coordinates = ANK_x , ANK_y), the toe (coordinates = TOE_x , TOE_y).

The following equations were used to compute the mass (M), and locations of the COM (X, Y) of different components of the TranTib prosthesis.

(1) COM of the socket (based on assumption (a))

$$X_S = TOS_x - 2/3 (TOS_x - BOS_x)$$

$$Y_S = TOS_y - 2/3 (TOS_y - BOS_y)$$

(2) COM of the lower leg (based on assumption (b))

$$X_{LL} = BOS_x - 1/2 (BOS_x - ANK_x)$$

$$Y_{LL} = BOS_y - 1/2 (BOS_y - ANK_y)$$

(3) COM of the foot (based on assumption (b))

$$X_F = ANK_x - 1/2 (ANK_x - TOE_x)$$

$$Y_F = ANK_y - 1/2 (ANK_y - TOE_y)$$

(4) Mass of the lower leg/foot component (based on assumption (b))

$$Mass_{LL} = Length_{LL} / (Length_S + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

$$Mass_F = Length_F / (Length_S + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

(5) COM of the prosthesis

$$X = \frac{Mass_S * X_S + Mass_{LL} * X_{LL} + Mass_F * X_F}{Mass_S + Mass_{LL} + Mass_F}$$

$$Y = \frac{\text{Mass}_S * Y_S + \text{Mass}_{LL} * Y_{LL} + \text{Mass}_F * Y_F}{\text{Mass}_S + \text{Mass}_{LL} + \text{Mass}_F}$$

APPENDIX E

Equations for Calculating Prosthesis Center of Mass for Transfemoral Athletes

To obtain the necessary measurements for calculating the COM of the components of the prosthesis, five digitized points for TranFem athletes in the XY plane of the prosthesis were used: top of the socket (coordinates = TOS_x , TOS_y), bottom of the socket (coordinates = BOS_x , BOS_y), the knee (coordinates = $KNEE_x$, $KNEE_y$), the ankle (coordinates = ANK_x , ANK_y), the toe (coordinates = TOE_x , TOE_y).

The following equations were used to compute the mass (M), and locations of the COM (X, Y) of different components of the TranFem prosthesis.

(1) COM of the socket (based on assumption (a))

$$X_S = TOS_x - 2/3 (TOS_x - BOS_x)$$

$$Y_S = TOS_y - 2/3 (TOS_y - BOS_y)$$

(2) COM of the pylon

$$X_P = BOS_x - 1/2 (BOS_x - TKNEE_x)$$

$$Y_P = BOS_y - 1/2 (BOS_y - TKNEE_y)$$

(3) COM of the top of the knee

$$X_{TK} = TKNEE_x - 1/2 (TKNEE_x - KNEE_x)$$

$$Y_{TK} = TKNEE_y - 1/2 (TKNEE_y - KNEE_y)$$

(4) COM of the bottom of the knee

$$X_{BK} = KNEE_x - 1/2 (BKNEE_x - ANK_x)$$

$$Y_{BK} = KNEE_y - 1/2 (BKNEE_y - ANK_y)$$

(5) COM of the lower leg (based on assumption (b))

$$X_{LL} = BKNEE_x - 1/2 (BKNEE_x - ANK_x)$$

$$Y_{LL} = BKNEE_y - 1/2 (BKNEE_y - ANK_y)$$

(6) COM of the foot (based on assumption (b))

$$X_F = ANK_x - 1/2 (ANK_x - TOE_x)$$

$$Y_F = ANK_y - 1/2 (ANK_y - TOE_y)$$

(7) Mass of the pylon

$$Mass_P = Length_P / (Length_S + Length_P + Length_{TK} + Length_{BK} + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

(8) Mass of top of knee

$$Mass_{TK} = Length_{TK} / (Length_S + Length_P + Length_{TK} + Length_{BK} + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

(9) Mass of bottom of knee

$$Mass_{BK} = Length_{BK} / (Length_S + Length_P + Length_{TK} + Length_{BK} + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

(10) Mass of the lower leg/foot component (based on assumption (b))

$$Mass_{LL} = Length_{LL} / (Length_S + Length_P + Length_{TK} + Length_{BK} + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

$$Mass_F = Length_F / (Length_S + Length_P + Length_{TK} + Length_{BK} + Length_{LL} + Length_F) * Mass_{PROSTHESIS}$$

(11) COM of the prosthesis

$$X = \frac{Mass_S * X_S + Mass_P * X_P + Mass_{TK} * X_{TK} + Mass_{BK} * X_{BK} + Mass_{LL} * X_{LL} + Mass_F * X_F}{Mass_S + Mass_P + Mass_{TK} + Mass_{BK} + Mass_{LL} + Mass_F}$$

$$Y = \frac{Mass_S * Y_S + Mass_P * Y_P + Mass_{TK} * Y_{TK} + Mass_{BK} * Y_{BK} + Mass_{LL} * Y_{LL} + Mass_F * Y_F}{Mass_S + Mass_P + Mass_{TK} + Mass_{BK} + Mass_{LL} + Mass_F}$$