Is Increased Residual Shank Length a Competitive Advantage for Elite Transtibial Amputee Long Jumpers?

Lee Nolan
Karolinska Institutet, Sweden

Benjamin L. Patritti
Harvard Medical School, USA

Laura Stana and Sean M. Tweedy
University of Queensland, Australia

The purpose of this study was to evaluate the extent to which residual shank length affects long jump performance of elite athletes with a unilateral transtibial amputation. Sixteen elite, male, long jumpers with a transtibial amputation were videoed while competing in major championships (World Championships 1998, 2002 and Paralympic Games, 2004). The approach, take-off, and landing of each athlete’s best jump was digitized to determine residual and intact shank lengths, jump distance, and horizontal and vertical velocity of center of mass at touchdown. Residual shank length ranged from 15 cm to 38 cm. There were weak, nonsignificant relationships between residual shank length and (a) distance jumped ($r = 0.30$), (b) horizontal velocity ($r = 0.31$), and vertical velocity ($r = 0.05$). Based on these results, residual shank length is not an important determinant of long jump performance, and it is therefore appropriate that all long jumpers with transtibial amputation compete in the same class. The relationship between residual shank length and key performance variables was stronger among athletes that jumped off their prosthetic leg ($N = 5$), and although this result must be interpreted cautiously, it indicates the need for further research.

**Keywords:** amputation, athletics, below knee, classification, paralympic, track and field

Lee Nolan is with the Laboratory for Biomechanics and Motor Control, Karolinska Institutet and the Swedish School of Sport and Health Sciences, GIH, Stockholm, Sweden. She is also with the Department of Rehabilitation at Jönköping University, Jönköping, Sweden. Benjamin L. Patritti is with the Department of Physical Medicine and Rehabilitation at Harvard Medical School in Boston, MA. He is also with the Department of Rehabilitation and Aged Care, Repatriation General Hospital, Adelaide, Australia. Laura Stana and Sean Tweedy are with the University of Queensland, School of Human Movement Studies in Brisbane Australia. Laura Stana is also with the Department of Rehabilitation Sciences at Katholieke Universiteit in Leuven, Belgium.
Sport can play an important, on-going role in the lives of persons with a lower limb amputation, providing a self-directed means of augmenting rehabilitation outcomes as well as offering opportunities for recreation, social interaction, and the pursuit of athletic excellence (Tweedy, 2002). Through initiatives of the International Paralympic Committee (IPC), amputees in more than 160 countries have the opportunity to participate in sport, from a recreational level to an elite international level (i.e., World Championships and Paralympic Games; IPC Athletics, 2007).

Athletics (track and field) is one of the most popular Paralympic sports and more than 7,000 athletes are registered internationally (International Paralympic Committee, 2005). The severity of impairments affecting eligible competitors varies tremendously and therefore, to ensure that athletes with less severe impairments do not gain a competitive advantage over those with more severe impairments, a system of classification has been developed. The stated purpose of the system is consistent with the IPC position stand on classification in Paralympic sport—to promote participation in sport by people with disabilities by minimizing the impact of impairment on the outcome of competition (Tweedy & Bourke, 2009; Tweedy & Vanlandewijck, 2011). To achieve this purpose, each class within the classification system should comprise athletes who have impairments that have a comparable impact on sports performance.

Currently, all persons with a transtibial amputation compete in the same class: T44 in track events and F44 in field events. The residual shank length of athletes in this class can vary considerably. Although studies evaluating the relationship between residual limb length and athletic performance have not been conducted, clinical evidence indicates that longer residual shank length confers some functional advantages. For example, increased residual shank length improves gait by providing a longer and stronger lever arm, improved prosthetic control, and a greater contact surface to support and stabilize the prosthetic socket (Bowker, 2004; Isakov, Burger, Gregoric, & Marincek, 1996; Radcliffe, 1994). Furthermore, research indicates that compared with persons with short residual shank lengths (< 15.1 cm), those with long residual shank lengths (> 15.1 cm) exhibit greater strength in the thigh muscles of the amputated leg (Isakov et al., 1996). It has also been shown that longer residual shank lengths are associated with increased walking distance (Pohjolainen & Alaranta, 1991) and reduced energy expenditure in walking (Gailey et al., 1994; Gonzalez, Corcoran, & Reyes, 1971).

While these studies clearly indicate that longer residual shank length confers clinical advantages, the participants in these studies were sedentary, participating in low-intensity activities. As a consequence, it is difficult to draw inferences from these studies regarding the effect of residual shank length on performance in elite athletics.

The athletic discipline of interest in this study was long jump. Key determinants of long jump include horizontal and vertical velocity of the whole body center of mass at touchdown—the point at which the athlete “touches down” on to the takeoff board in the takeoff stride (Hay, 1993; Lees, Fowler, & Derby, 1993; Lees, Graham-Smith, & Fowler, 1994). High horizontal velocity at touchdown is strongly associated with greater jump distance (Hay, 1993; Lees, Fowler, & Derby, 1993; Lees, Graham-Smith, & Fowler, 1994). Vertical velocity at touchdown may be positive or negative—a high negative vertical velocity is associated with decreased jump distance (Lees, Graham-Smith, & Fowler, 1994). It has been demonstrated that negative vertical velocity tends to be greater among persons with transfemoral
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amputation than persons with transtibial amputation and greater among persons with transtibial amputation than among nondisabled athletes (Nolan & Lees, 2000). Nolan and Lees hypothesized that greater negative vertical velocity may be related to characteristics of the prosthetic/residual limb, but it is not known whether vertical velocity is affected by residual limb length.

The purpose of this study was to determine whether residual shank length affects long jump performance of elite athletes with unilateral transtibial amputation. Specifically, this study assessed the relationship between residual shank length and (a) distance jumped, (b) horizontal velocity of the center of mass at touchdown, and (c) vertical velocity of the center of mass at touchdown. A weak relationship between residual shank length and these key performance determinants will indicate that class T/F44 is achieving its intended purpose—to minimize the impact of impairment on the outcome of competition.

Method

Participants

Data were collected on elite male athletes competing in long jump events in three major athletics championships between 1998 and 2004. Inclusion criteria, to obtain a group with as little influence from performance ability and prosthesis type as possible, were the following: any athlete competing in the F44 (long jump for persons with transtibial amputation) and P44 (pentathlon long jump event for persons with transtibial amputation) finals at the 1998 and 2002 World Disabled Athletics competitions and the 2004 Paralympic Games; had a unilateral transtibial amputation; and used a carbon fiber sprint type prosthesis and were able to jump at least 5m. The last criteria was used to exclude any athletes competing in the P44 finals who were skilled in other pentathlon events but not considered to be elite long jumpers. From the three competitions, 16 athletes met these criteria. Eleven jumped off their intact limb and five off their prosthetic limb. Due to the competition being a public broadcast performance, no institutional ethical approval was needed to film the event. All data obtained were handled with ethical consideration by the authors.

Apparatus and Procedure

The long jump competitions in all three championships were filmed in the same way. A video camera recording sagittal plane movements at 50 Hz was placed so that the last stride, touchdown onto the take-off board and take-off, or part of take-off were visible. The jumps were filmed using a Panasonic VHS video camera (in 1998), a JVC digital video camera model DVL9700 (in 2002), or a Sony digital video camera model DCR-TRV33E (in 2004). Before all competitions, a calibration frame was filmed in the sagittal plane to later perform a two-dimensional biomechanical analysis. During competition, the camera was left running and the athletes’ jumps recorded. Official distance was documented for every jump.

Data Analysis

The best jump (greatest official distance) of each athlete was analyzed and three performance parameters were derived (a) effective distance jumped, (b) horizontal
velocity of the whole body center of mass at touchdown ($V_{\text{hor}}$), and (c) vertical velocity of the whole body center of mass at touchdown ($V_{\text{ver}}$). Effective distance was calculated by adding official distance to the toe-to-board distance, which was measured from sagittal plane video. $V_{\text{hor}}$ and $V_{\text{ver}}$ were derived by digitizing with either eHuman digitizing software (HMA Technology, Inc, Ontario, Canada) or custom written software, both of which use the same standard 9-segment biomechanical model defined by 18 points. The digitized coordinates for the endpoints of individual body segments were recorded and center of mass was determined based on anthropometric norms for adult males (Dempster, 1955), modified to account for the prosthetic limb (Nolan & Lees, 2000). Data were smoothed using a Butterworth digital filter and a cut-off frequency of 7 Hz. The instant of touchdown (TD) was taken as the first frame in which the foot was clearly seen to be in contact with the ground.

Residual shank length and the corresponding intact shank length were measured from video. The residual shank length was measured from the knee joint center to the end of the socket of the prosthesis, and intact shank length was measured from the knee joint center to the ankle joint center. Residual shank lengths were expressed in (a) absolute length (centimeters) and (b) residual shank length as percentage of intact shank length. Residual and intact shank lengths were determined independently by each of two investigators. When expressing residual shank length as percentage of shank length, less than 1.5% difference in calculations between the two investigators was found.

Digitizing error due to using 50Hz instead of a faster sampling frequency has previously been determined for amputee athletes (Nolan, Patritti, & Simpson, 2006). The magnitude of this error was found to be smaller than the intersubject variation for athletes with an amputation. Normality of data was tested using Shapiro-Wilk. Pearson product moment correlation coefficients ($r$) were calculated to assess the strength of relationships between residual shank length and (a) effective distance jumped, (b) $V_{\text{hor}}$ and (c) $V_{\text{ver}}$. The significance level used for all correlations was set at alpha = 0.05.

**Results**

Table 1 presents residual and intact shank lengths and jump performance descriptors for each athlete. The official jump distance ranged from 5.04 m to 6.79 m, the latter being the current world record for persons with a transtibial amputation. Residual shank length ranged from 15 cm to 38 cm (34–98% of the intact shank length).

The relationship between each of the three performance parameters and residual shank length was similar, regardless of whether absolute residual shank length (cm) or percentage of intact shank length was used. Therefore, only results for absolute residual shank length (cm) are reported.

Figure 1 illustrates the weak relationship between residual shank length (cm) and effective distance jumped for all athletes ($r = 0.30$). Figure 2 indicates that $V_{\text{hor}}$ ranged from 5.6 to 9.4 m.s$^{-1}$. The relationship between $V_{\text{hor}}$ and residual shank length was also weak ($r = 0.31$). Figure 3 indicates that $V_{\text{ver}}$ ranged from 0.7 to 0.6 m.s$^{-1}$ and there was no relationship between $V_{\text{ver}}$ and residual shank length ($r = 0.05$). None of the correlations were statistically significant.
<table>
<thead>
<tr>
<th>Athlete</th>
<th>Residual Shank Length (cm)</th>
<th>Intact Shank Length (cm)</th>
<th>Residual Shank Length (% Intact Shank Length)</th>
<th>Official Jump Distance (m)</th>
<th>Championship</th>
<th>Take-Off Leg</th>
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<tr>
<td>1</td>
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<td>5.04</td>
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<td>Intact</td>
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<tr>
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<td>5.88</td>
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<tr>
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<td>Intact</td>
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Note. None of the excluded athletes (did not jump over 5m see inclusion criteria) had a residual shank length of 15cm or less.
Figure 1 — Relationship between absolute residual shank length and effective distance jumped. (Linear regression includes ALL athletes, but for purpose of displaying choice of take-off limb, those taking off from their prosthetic limb are indicated by open circles, while those taking off from their intact limb are indicated by solid circles.)

Figure 2 — Relationship between absolute residual shank length and horizontal velocity of center of mass (m.s\(^{-1}\)) at touchdown. (Linear regression includes ALL athletes, but for purpose of displaying choice of take-off limb, those taking off from their prosthetic limb are indicated by open circles, while those taking off from their intact limb are indicated by solid circles.)
The results of this study indicate that the long jump performance of the athletes with unilateral transtibial amputation in this study is not affected by residual shank length. Specifically, this study demonstrated that there was only a weak relationship between residual shank length and effective jump distance. The lack of association is unlikely to be explained by a restricted data range (see Figure 1).

Examination of the data in Table 1 indicates that athletes with a wide range of residual shank lengths compete at the international level. To wear a transtibial prosthesis, active knee flexion and extension must be possible and the residual limb must be sufficiently long to permit the musculature to control a prosthesis. The most proximal transtibial amputation that will preserve flexion / extension is just below the tibial tubercle—at this level insertion of the quadriceps remains intact, as does insertion of semimembranosus and biceps femoris (Bowker, 2004). Most surgeons believe, however, that amputation at the tibial tubercle does not preserve sufficient lever length to achieve satisfactory everyday functioning and opinion regarding the minimum residual length varies from 9–15 cm (Bowker, 2004; Carnesale, 2003).

In the current study, the absolute length of residual limbs range from 15cm to 38 cm and relative length ranges from 34% to 98% of the intact limb. The absence of athletes with residual limbs less than 15 cm in our sample suggests the possibility that athletes with very short residual limbs (e.g., ≤ 10cm) are not competitive at the international level, likely due to compromised stability of the prosthetic socket (Isakov, Maizrahi, Susak, & Onna, 1992). However, the presence of three athletes

**Discussion**

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with residual shank lengths of 15–17 cm in this sample indicates that even athletes with residual limbs that are close to what is considered the clinically minimum length can compete successfully at the highest level. It is interesting to note that one of the athletes with a very short residual limb (17 cm) had the second longest jump of the group and jumped over 6 m (Table 1). These data seem to indicate that persons with a transtibial amputation that have a minimum residual shank length of 15 cm do not have a disadvantage in long jump performance compared with those with a longer residual shank length when competing at elite level.

The veracity of this result is strengthened by the fact that two key determinants of long jump performance—horizontal and vertical velocity of center of mass—were, respectively, weakly or unrelated to residual shank length. Horizontal velocity has previously been shown to correlate positively with jump distance in both able-bodied (Hay, 1993; Lees, Graham-Smith, & Fowler, 1994) and amputee (Nolan & Lees, 2000) long jump. Thus if the length of the residual shank had an effect on either run up speed or long jump distance, a strong positive correlation would have been seen. The resulting weak correlation in this study of $r = 0.31$ indicates this is not the case.

A high negative vertical velocity is associated with reduced control at touchdown and is detrimental to long jump performance (Lees, Graham-Smith, & Fowler, 1994). If reduced residual shank length adversely affected performance, through instability or loss of control either when touching down onto the prosthetic limb or as a result of a problem pushing off from the prosthetic limb and landing onto the intact limb, it would be associated with high negative $V_{vert}$ values; however, this was not seen with the athletes in this study (see Figure 2 and 3). Thus the lack of correlation between residual shank length and $V_{vert}$ ($r = 0.05$) indicates that a lack of control at touchdown has no relation to residual shank length.

It should be noted that the data set presented is ideal for examining the research question posed. Each athlete was of international standard and each jump analyzed was an international personal best for that athlete at that time. By presenting the best jump from 16 of the best elite transtibial long jumpers in the world over a six-year period, a range of sources of interathlete variation were considerably reduced, including poor conditioning, poor technique and suboptimal equipment. The only athletes excluded from this dataset were the ones who competed in the pentathlon at international level but failed to perform well in the long jump (jumped less than 5 m). Excluding these two athletes ensured poor conditioning and/or poor technique did not skew the results. All the athletes competing in the finals at international level used a carbon fiber sprint type prosthesis. It may be that athletes who do not have access to such a prosthesis cannot reach the performance level required for the final and may have been excluded for this reason. As the prosthesis type can affect performance to some degree, however, excluding these and including the majority who used a similar “optimal” prosthesis type resulted in a more homogeneous dataset. Reducing sources of interathlete variation ensured that the proportion of variation attributable to residual shank length was maximized and the possibility of a false negative finding was minimized.

In recent years, technology has improved the energy storing capacity of prosthetic legs to the extent that some athletes have elected to jump off their prosthesis rather than their intact leg. Five of the 16 athletes in our sample jumped off their prosthetic leg (see Table 1 and Figures 1–3). Obviously, athletes who use this
technique greatly increase the physical demands on their residual limb compared with those who jump off their intact leg.

If the five athletes who jumped off their prosthetic leg are analyzed in isolation, correlations indicate that residual shank length accounted for 21.5% of the variance in effective jump distance, 38% of the variance in horizontal velocity of the center of mass, and 73% of the variance in the vertical velocity of the center of mass. It is important to note that these results must be interpreted cautiously—the sample was small ($n = 5$) and results were all nonsignificant. However, the results do indicate that, in relation to athletes who jump off their prosthetic leg, further research investigating the relationship between residual shank length and performance is warranted.

In summary, residual shank length had no effect on distance jumped or velocity at touchdown for the elite male long jumpers with transtibial amputation in this study. As this data set included athletes with residual shank lengths ranging from the shortest preserved length recommended by surgeons (15cm) to through ankle amputation, it can be concluded that it is not the residual shank length that affects long jump performance; rather, it is suggested that ability, technique, prosthesis, and training plays a more important role. It is noteworthy that the relationship between residual shank length and key performance variables was stronger among athletes that jumped off their prosthetic leg. Although the small sample size ($N = 5$) requires that this result be interpreted cautiously, it indicates the need for further research in this area.

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