A BIOMECHANICAL ANALYSIS OF THE TAKE-OFF PHASE IN BELOW-KNEE AMPUTEE HIGH JUMP

Lee Nolan[1], Benjamin L. Patritti[2] and Kathy J. Simpson[3]
[1]Laboratory for Biomechanics and Motor Control, Karolinska Institutet and University College of Physical Education and Sports, Stockholm, Sweden
[2]Department of Physical Medicine and Rehabilitation, Spaulding Rehabilitation Hospital, Harvard Medical School, Boston, MA, USA
[3]Department of Kinesiology, University of Georgia, Athens, GA, USA

An analysis of below-knee amputee take-off technique was performed on two athletes competing in the high jump finals of the 2004 Paralympic Games. Two digital video cameras were used to film the event with the data later digitised and reconstructed using standard 3-D DLT procedures. Some similarities with non-amputee high jump technique were noted in that centre of mass height was low at touch-down (TD), there was a similar reported magnitude of negative vertical velocity at TD, and most of the vertical velocity generated occurred in the first half of the take-off phase. However, both below-knee amputee athletes exhibited a slower horizontal approach velocity, a lower positive vertical take-off velocity, a more upright leg position at touch-down and a greater range of motion of the hip throughout the take-off phase compared to what is known about non-amputee high jump technique. These differences may be associated with taking off from the prosthetic limb on the last stride of approach. Understanding why these differences occur has implications for coaching and improving technique.

KEY WORDS: high jump, amputee, biomechanics, technique, below-knee

INTRODUCTION: Identifying the biomechanical elements associated with success in the high jump for elite amputee performers has not been undertaken, although there exists a solid body of evidence for non-amputee performers (Dapena, 1987; Greig and Yeadon, 2000; Dapena and Chung, 1988; Papadopoulos et al. 1995; Conrad and Ritzdorf, 1988). These studies have shown that when using the Fosbury flop jump technique, the purpose of the approach run is to set the appropriate conditions for the take-off phase (Dapena, 1988), and that peak height of the centre of mass (CM) over the bar is dependent on the height and vertical velocity of the CM at take-off. This in turn is dependent on approach speed and the position of the body at touch-down. Elite below-knee amputees (BKA) who perform the flop technique may display adaptations to the constraints associated with the use of a prosthetic limb. If so, the nature of the adjustments and the purposes they serve has implications for coaching and training. Thus, the aim of this study was to analyse the high jump technique used by elite BKA athletes.

METHODS: The final of the mens F44-F46 high jump competition at the 2004 Paralympic Games was filmed using two 50 Hz digital video cameras (Sony, model DCR-TRV33E) placed perpendicular to each other so that the last stride and take-off were visible in both cameras, regardless of which side the athlete approached the high jump mat. Before competition, a 3-D 18 point calibration frame was placed and filmed at several positions in front of the high jump mat. Two of the eleven competitors in the final were below-knee amputees (BKA) who used a prosthesis and were thus included in the study.
All successful jumps were digitised for each BKA, using eHuman digitising software (HMA Technology, Inc, Ontario, Canada) and a 9 segment model defined by 18 points. The segmental data used (Dempster, 1955) for adult males were modified for each athlete to account for the prosthetic limb (Nolan and Lees, 2000). As measurements of the athletes' heights were not available, estimated height for each athlete was calculated as the sum of the length of the individual intact segments (Hay and Nohara, 1990) from the digitised data. Co-ordinate data for the intact limb only was used as athletes can set their prosthetic limb length slightly longer or shorter than their intact limb depending on personal preference. The 3-D co-ordinates of the digitised points were generated (standard DLT) and filtered using a

Butterworth 4th order filter with a cut-off frequency of 7 Hz based on a residual analysis and visual inspection (Winter, 1990). Key events in the high jump, defined by previous analysis of elite non-amputee athletes, were determined for each jump; centre of mass height normalised to individual height (H_{CM}), horizontal (V_{horiz}) and vertical velocity (V_{vert}) of the centre of mass, hip angle, knee angle and leg angle at touch-down (TD), maximum knee flexion (MKF) and take-off (TO). All were calculated in the athletes' sagittal plane. The hip and knee angles were defined as the included angle between shoulder, hip and knee, and hip, knee and ankle respectively. The leg angle was defined as the angle made by the line joining the CM and the ankle to the vertical. Finally, changes in the above-mentioned variables in the first half (TD-MKF) and second half (MKF-TO) of the take-off phase were calculated. As there were only 2 below-knee amputees in the competition, it was not possible to perform a statistical analysis. Descriptive data will be used to characterise the BKA high jump technique.

RESULTS AND DISCUSSION: Both athletes used a curved approach run. Athlete 1 had a personal best of 2.09 m and athlete 2 a personal best of 1.88 m. Both athletes took off from their intact leg. Athlete 1 performed 3 successful jumps, while athlete 2 performed 2 successful jumps.

Approach velocities: There was no quantitative relationship between horizontal velocity at TD, MKF or TO or vertical velocity at TD, MKF or TO and successful height jumped for the two BKA (Figure 1). In contrast, Greig and Yeadon 2000) and Dapena (1987) noted a positive relationship between approach velocity and jump height for non-amputee athletes. This may suggest that these two BKA athletes are unable to fully convert their horizontal approach velocity to vertical velocity and thus maximise height jumped, possibly due to a differing touch-down/ take-off technique from non-amputee high jumpers.

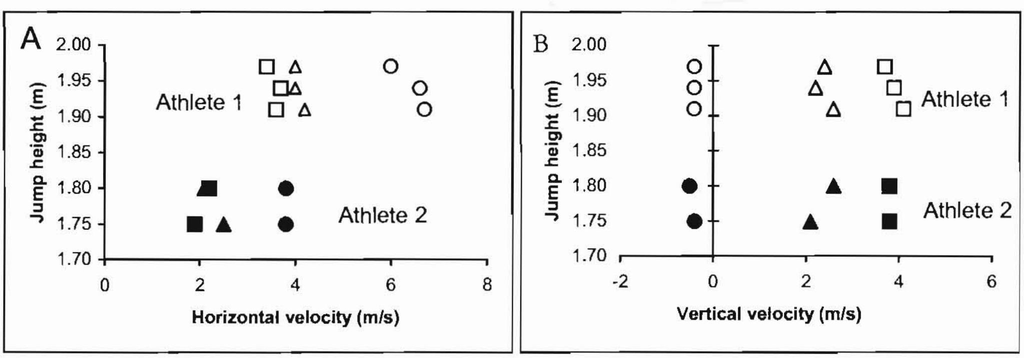

Figure 1 a) horizontal velocity and b) vertical velocity at TD (circle), MKF (triangle) and TO (square) for successful height jumped.

Both BKA exhibited slower horizontal velocity than previously reported for non-amputee high jumpers (Table 1). This was expected due to constraints associated with a prosthesis, i.e., lack of ankle musculature that reduces propulsive force and may influence the ability to modulate foot placement location and timing at TD. Vertical velocity at TD was of similar magnitude to non-amputee high jumpers (Table 1). The negative vertical velocity at TD is due to the athlete exerting a large downward force on the ground in order to obtain a large upward vertical reaction force at the end of the take-off phase (Dapena, 1987). The positive vertical velocity at TO, however, was slightly lower for the amputee athletes than that reported for non-amputee athletes, suggesting that the lack of a relationship between vertical velocity at TO and height jumped by these amputee athletes may stem from problems developing a high vertical impulse during the take-off phase. Vertical take-off velocity is dependent on the horizontal velocity developed in the approach and the effectiveness in which it is converted to vertical velocity during the take-off phase (Dursenev, 1991). Non-amputee athletes increase vertical velocity during the first half of the take-off phase (TD-MKF) as a result of the large forces at TD associated with eccentric muscle conditions (Dapena and Chung, 1988), but at the expense of a loss in horizontal velocity. Hence, most of the vertical velocity is generated, and consequently, most of the horizontal velocity is lost, in the first half of the take-off phase (TD-MKF). This is also exhibited by BKA (Table 1).

Table 1 Selected high jump variables at TD, MKF and TO (means) for two BKA.

Variable	Athlete 1	Athlete 2	Non-amputee athletes
TD V_{horiz}	6.4 $m.s^{-1}$	3.9 $m.s^{-1}$	7.4^{*}, 6.9^{**}, $7.02^{\dagger}$, $6.7^{\dagger\dagger}$ $m.s^{-1}$
TO V_{horiz}	3.6 $m.s^{-1}$	2.1 $m.s^{-1}$	3.9 $m.s^{-1*}$
% V_{horiz} lost (TD-MKF)	82.4%	84.2%	
% V_{horiz} lost (MKF-TO)	17.6%	15.8%	
TD V_{vert}	-0.4 $m.s^{-1}$	-0.5 $m.s^{-1}$	-0.4^{*}, $-0.1^{\dagger\dagger}$, -0.2—0.9 $m.s^{-1\,x}$
TO V_{vert}	3.9 $m.s^{-1}$	3.8 $m.s^{-1}$	4.2^{*}, 4.65^{**}, $4.0^{\dagger\dagger}$, 4.5-5.0 $m.s^{-1x}$
% V_{vert} gained (TD-MKF)	65.1%	65.8%	
% V_{vert} gained (MKF-TO)	34.9%	34.2%	
H_{CM} TD (% of height)	49.6%	50.3%	46-49.5%*
H_{CM} MKF (% of height)	54.7%	50.3%	
H_{CM} TO (% of height)	73.5%	69.9%	
$Knee_{ang}$ TD	155°	157°	$168^{\circ**}$, $171\text{-}177^{\circ\dagger}$, $165\text{-}175^{\circ x}$
$Knee_{ang}$ MKF	128°	129°	$160^{\circ**}$, $130\text{-}155^{\circ x}$
$Knee_{ang}$ TO	164°	172°	$175^{\circ**}$
Hip_{ang} TD	143°	143°	
Hip_{ang} MKF	146°	149°	
Hip_{ang} TO	180°	176°	

*Dapena (1987) **Papadopoulos et al. (1995) †Greig and Yeadon (2000)
††Dapena and Chung (1988) ^{x}Conrad and Ritzdorf (1988)

Centre of mass height: The mechanism in which horizontal velocity is converted to vertical velocity requires a low centre of mass position at TD (Dapena, 1987). If the horizontal approach velocity is too fast or the CM position is too low for the amount of eccentric leg strength the athlete has, the leg will 'buckle' resulting in a failed jump (Dapena, 1987). Thus there is an optimum relationship between approach velocity and CM height for each athlete. The two amputee athletes exhibited a similarly low centre of mass position at TD as is reported for elite non-amputee high jumpers, a high H_{CM} was seen at TO and no 'buckling' of the leg was observed. Thus the reason for not generating as much vertical velocity at TO as non-amputee high jumpers is possibly not due to inadequate eccentric leg strength.

Joint kinematics: In order to have a low CM at TD, an athlete can either increase knee flexion or increase stride length. In this study, no relationship between knee angle at TD and height jumped was found (Figure 2). Such a relationship was reported for an elite non-amputee athlete (Greig and Yeadon, 2000), but this could be due to individual technique, strength or ability. A relationship was qualitatively visible between leg angle at TD and height jumped for both BKA i.e. the smaller the leg angle (the less far in front of the body the TD leg was placed), the greater height jumped (Figure 3). This contrasts with that reported for non-amputee high jumpers (Dapena 1987; Greig and Yeadon, 2000), but similar to amputee long jumpers (Nolan and Lees, 2000). If the take-off leg is planted well ahead of the body at TD, a large vertical impulse is provided, maximising vertical velocity at TO (Dapena, 1987). Hence this might explain why less vertical velocity at TO was generated by the amputee athletes compared to non-amputee high jumpers. The more upright leg TD position seen for the amputee athletes could be due to taking off from their prosthetic leg on the previous stride.

The amputee athletes also touched-down with a flexed hip. This position is caused by a slightly upright position of the trunk i.e. the amputee athletes are not leaning backwards at TD. A backward lean of the trunk at TD has been suggested to be advantageous as it evokes a stretch reflex which may increase the force that the muscles can exert in the second half of the take-off phase (Dapena and Chung, 1988). Thus the BKA are unable to utilise this advantage. Instead, the amputee athletes, because they land with a less extended touch-down leg compared to non-amputee athletes, they may be using the hip more in compensation to provide a greater range of motion during the take-off phase (TD-TO) in order to generate more vertical velocity and height at TO. This strategy has previously been seen in elite amputee long jumpers (Nolan and Lees, 2000).

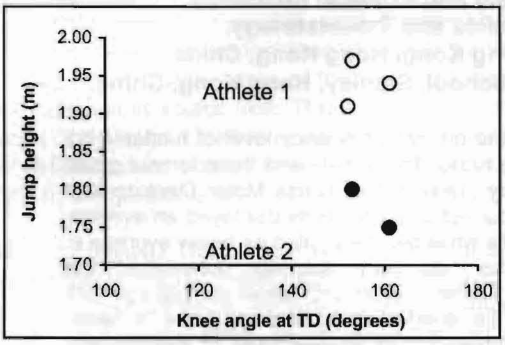

Figure 2 Knee angle at TD versus jump height.

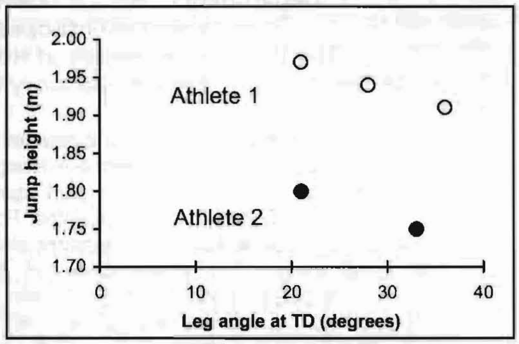

Figure 3 Leg angle at TD versus jump height.

CONCLUSION: While it is not possible to generalise these findings to all BKA jumpers, this study has provided some insight to the techniques displayed by a group of elite athletes not previously studied. Although the technique of any BKA jumper demonstrates some unique characteristics due to differing levels of amputation, strength, ability and prostheses used, these two athletes exhibited some shared kinematics that also differed from what is known about non-amputee high jump technique. These observations provide a first insight to understanding the mechanisms underlying BKA high jump technique which has implications for training and coaching.

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