INTRA-INDIVIDUAL JOINT ANGLE VARIATION DURING THE TAKE-OFF STEP OF LONG JUMPERS WITH TRANSTIBIAL AMPUTATION – PRELIMINARY RESULTS

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Biomechanical knowledge of the long jump take-off step is not comprehensive for athletes with below the knee amputation (BKA), yet it is important for improving training protocols and performance. Three-dimensional motion capture (Vicon) and a mathematical rigid-body model (Dynamicus, Alaska) were used to calculate joint angles during repeated long jump take-off steps of athletes with and without BKA. Preliminary results indicate that those athletes with BKA who perform better during the long jump compared to another athlete with BKA, have relatively high intra-individual joint angle variation at the knee and hip joint at the instant of take-off compared to non-amputee athletes. The presented results may stimulate future research questions and can inform athletes and coaches during the development of training protocols.

KEYWORDS: Athletics, kinematics, prosthetics, knee joint, motor control, performance

INTRODUCTION: Little is known about the take-off step kinematics of long jumpers with below the knee amputation (BKA) who use their affected leg for the take-off step and have competed within the past 5 years. During the 2004 Paralympic Games, Nolan, Patritti, & Simpson (2012) analyzed the long jump kinematics of athletes with BKA who used their affected leg as their take-off leg (n=5, average jump distance = 6.04 m). They found that the take-off technique of these athletes mimics the use of a 'springboard' (Nolan et al., 2012), instead of the pivot strategy used by non-amputee athletes (Lees, Graham-Smith, & Fowler, 1994). Today, almost all elite long jumpers with BKA take off from their affected leg and the current men's world record is 8.48 m.
The run-up of the long jump requires high accuracy for a valid take-off board strike (Linthorne, 2008) and athletes might need to make small adjustments to the aligment of their take-off leg to react to smaller imprecisions. Instead of three biological joints, the affected leg of athletes with unilateral BKA comprises two biological joints and a running-specific prosthesis (RSP), which functions as a mechanical spring. Thus, athletes with BKA have one less joint to actively adjust the alignment of their take-off leg. This could lead to greater intra-individual variation in the hip and knee joint angles, due to the need for greater adjustments in the respective joints, compared to non-amputee athletes. However, to our knowledge no previous study has analyzed the intra-individual joint angle variation throughout the take-off step in athletes with BKA. The purpose of this study, therefore, was to identify intra-individual kinematic variations at the joint level in long jumpers with BKA and compare them to non-amputee athletes.

METHODS: Three athletes with unilateral BKA and seven non-amputee athletes volunteered. All athletes were asked to perform three to six maximum distance long jumps. If an athlete performed more than six jumps we included all jumps that we were able to process. One non-amputee athlete only completed one valid jump. Due to the purpose of the current analysis, we excluded this athlete and thus present data from a total of nine athletes with an average personal record at the time of study of 7.43 ± 0.99 m (athletes with BKA) and 7.50 ± 0.57 m (non-amputee athletes). One athlete with BKA participated on two different dates, which are indicated as BKA2 and BKA2b. All long jumpers with BKA used their affected leg for the take-off step. Data collection for athletes BKA3 and BKA2b was performed at the Japanese Institute of Sport Sciences, while data collection for all other athletes took place at the German Sport University Cologne.

Spherical retro-reflective markers were attached to anatomic reference points of each athlete's body and on the prothesis. Marker trajectories were captured using a three-dimensional motion capture system (VICON^{TM}, Oxford, UK) and were filtered with a recursive fourth order Butterworth filter (cut-off: 50 Hz). Ground contact was defined as the first frame the foot or prosthesis touched the ground (touch-down: TD) through the last frame the foot or prosthesis had contact with the ground (toe-off: TO). Joint angles were calculated using a modified mathematical multi-body model (Dynamicus, Alaska, The Institute of Mechatronics, Chemnitz, Germany) and express the rotation of the distal relative to the proximal segment of the respective joint. Specific details of the multi-body model are presented in Willwacher et al. (2017). Effective jump distances were calculated from the most distal part of the shoe or the front edge of the RSP of the take-off leg at the instant of TO to the closest mark in the sand made by the athlete during landing (Nixdorf & Brüggemann, 1990). The position of the most distal part of the shoe was calculated using the horizontal position of the toe marker and an approximated 5 cm horizontal correction due to the marker positioning on the toe-box of the shoe above the second metatarsal joint. The position of the prosthesis' edge was calculated using the average horizontal position of two markers attached to the prosthesis and an approximated 0.5 cm horizontal correction due to marker radius. Due to the preliminary nature of the current analysis we performed descriptive, but not inferential statistics.

RESULTS AND DISCUSSION: All non-amputee athletes had discontinuous hip extension, whereas BKA1 and BKA2(b) had continuous hip extension throughout the stance phase of the take-off step in most trials (Fig. 1). Knee flexion angle at TD, in general, was lower for athletes with BKA compared to the non-amputee athletes but was very consistent (intra-individual standard deviation ≤ 2°) between trials in both groups of athletes (Tab. 1). At the instant of TO, the non-amputee athletes had relatively small intra-individual knee joint angle variation compared to BKA1 and BKA2(b) who had intra-individual knee joint angle variation ranging from 0-27° (BKA1), -2-24° (BKA2) and 22-42° (BKA2b).

Table 1. Mean values and standard deviation (SD) for stance time and effective jump distance as well as for knee and hip joint angles at the instances of touch down (TD), maximum knee flexion (MKF) and toe-off (TO) of athletes with below the knee amputation (BKA) and non-amputee athletes (nonAMP).

	Knee Flexion Angle [°]			Hip Flexion Angle [°]				
Athlete	TD	MKF	TO	TD	MKF	TO	Stance time [ms]	Effective jump distance [m]
BKA2 (n=7)	7 (1)	30 (4)	12 (9)	10 (2)	-2 (3)	-26 (5)	114 (3)	7.68 (0.14)
BKA2b (n=5)	6 (2)	38 (7)	31 (8)	10 (3)	-6 (5)	-17 (7)	113 (2)	7.37 (0.10)
BKA1 (n=4)	13 (1)	31 (6)	15 (12)	15 (2)	5 (2)	-14 (6)	121 (2)	6.82 (0.22)
BKA3 (n=3)	7 (1)	28 (4)	2 (5)	17 (1)	11 (2)	-19 (3)	141 (3)	6.04 (0.13)
nonAMP3 (n=7)	14 (1)	48 (1)	6 (2)	20 (2)	20 (2)	-24 (3)	119 (6)	7.06 (0.11)
nonAMP4 (n=7)	20 (2)	52 (4)	5 (2)	27 (4)	30 (2)	-23 (2)	135 (7)	6.99 (0.10)
nonAMP6 (n=5)	15 (2)	47 (3)	5 (3)	23 (1)	27 (2)	-25 (2)	114 (5)	6.95 (0.11)
nonAMP5 (n=6)	11 (1)	43 (3)	-3 (1)	12 (2)	16 (3)	-35 (2)	119 (3)	6.93 (0.07)
nonAMP2 (n=4)	13 (1)	50 (3)	4 (2)	20 (3)	24 (0)	-31 (2)	112 (7)	6.62 (0.14)
nonAMP1 (n=9)	17 (2)	47 (4)	2 (4)	25 (3)	23 (6)	-30 (2)	132 (8)	6.00 (0.13)

Positive values indicate flexion and negative values indicate extension of the respective joint.

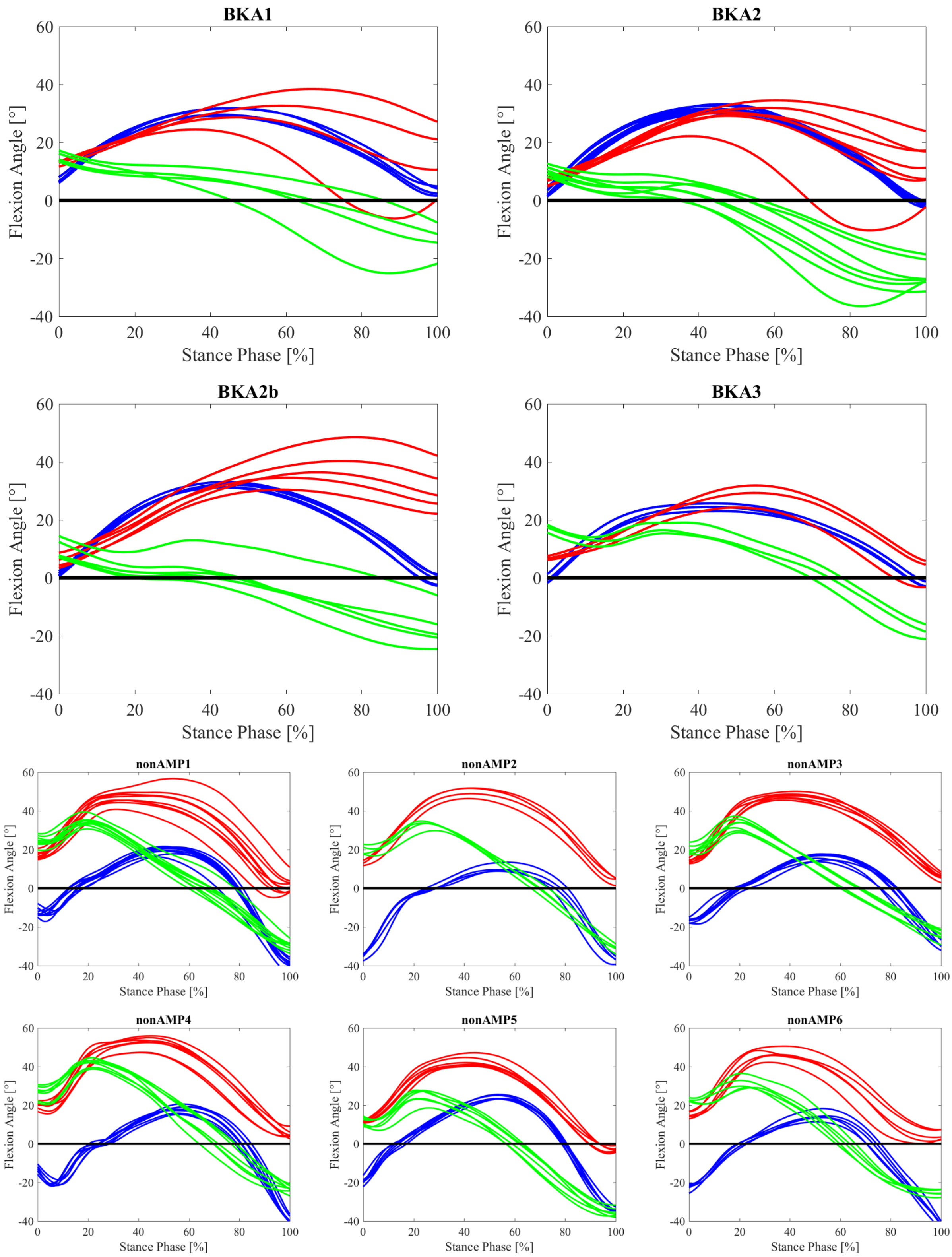

Figure 1: Sagittal plane joint angles of the ankle (blue), knee (red) and hip (green) during the take-off step for athletes with below the knee amputation (BKA) and non-amputee athletes (nonAMP). Positive values indicate flexion and negative values indicate extension of the respective joint. Stance phase is time-normalized to the duration of ground contact.

BKA3 jumped the shortest distance of the three athletes with BKA, had discontinuous hip extension similar to the non-amputee athletes, had similar knee joint angles at TD compared

to BKA2(b), but had lower intra-individual variation of the knee joint angle at TO compared to BKA1 and BKA2(b).
In two exemplary trials, BKA2 jumped very similar distances of 7.75 m and 7.71 m with knee TO angles of 7° and 24°, respectively. Similar results were observed for two exemplary trials of BKA1 who jumped 7.02 m and 6.94 m with knee joint angles at TO of 27° and 11°, respectively. Athletes with BKA do not seem to adjust their leg alignment at TD but adjust it later during the take-off phase (Fig. 1, Tab. 1). At the instant of TO, the variation of knee and hip joint angles appears to be higher in athletes with BKA compared to non-amputee athletes (Fig. 1, Tab. 1). This might be a response to the (anticipated) orientation of RSP extension in relation to the center of mass position, which in turn is likely affected by various kinematic parameters (e.g. movement speed, center of mass position and take-off leg alignment at the instant of TD). Thus, when neglecting the influence of different run-up speed between the three athletes with BKA, the high intra-individual joint angle variation of BKA1 and BKA2(b), especially in the knee, might indicate an enhanced ability to quickly adjust the take-off leg segmental alignment (Wilson, Simpson, Van Emmerik, & Hamill, 2008), in order to use the prosthesis to full capacity. This hypothesis should be investigated in future research by including aspects at the motor control level. However, it is already known from a previous study (Willwacher et al., 2017), that the prosthesis is of major importance for the energy storage and return during the take-off step of athletes with BKA, whereas there is only a minor energy change in the knee joint.
From a motor control perspective, future research could investigate potential changes in neurological requirements (e.g. motor unit recruitement) for executing the take-off step of the long jump for athletes with BKA compared to non-amputee athletes. Having one less biological joint to actively adjust the segmental aligment of the take-off leg during the long jump take-off step could be more demanding because of the reduced potential to realize necessary adjustments compared to having three biological joints that have more degrees of freedom. However, based on Bernstein (1967) it might be less demanding to have two versus three biological joints, because athletes with BKA have one less joint to adjust and therefore potentially have more motor control capacity for an optimized movement execution in the other biological joints.

CONCLUSION: At the instant of TO for the take-off step of the long jump, the intra-individual joint angle variation, especially in the knee, appears to be higher in athletes with BKA compared to non-amputee athletes. Extension of the knee joint during the take-off step may not influence jump distance for long jumpers with BKA because similar jump distance can be achieved with different knee angles at TO. Our results provide important information for athletes and coaches to adapt training protocols and enhance long jump performance.

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