FRONTAL PLANE TAKE-OFF STEP MECHANICS OF LONG JUMPERS WITH AND WITHOUT A BELOW THE KNEE AMPUTATION

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Frontal plane mechanics during the long jump take-off step are unknown for athletes with and without a transtibial amputation. This is an issue due to the importance of the knowledge for training and rehabilitation protocols or prosthetic design. In this study the take-off step of three long jumpers with and seven without a below the knee amputation (BKA) were analysed with regard to frontal plane mechanics. Three-dimensional motion capture (Vicon) and a force plate (Kistler) were used to capture kinematic and kinetic data. Inverse dynamic calculations (Dynamicus, Alaska) revealed differences in frontal plane center of mass kinematics and joint kinetics between groups. Specifically, athletes with BKA had lower medio-lateral ground reaction forces, lower frontal plane joint loads and an altered foot position pattern compared to non-amputee athletes.

KEYWORDS: GRF, athletics, COM kinematics, prosthetics, energy, joint moments

INTRODUCTION: The long jump, just like walking or sprinting, is primarily conducted in the sagittal plane (Hay, 1986; Alt, Heinrich, Funken & Potthast, 2015). However, muscles majorly operating in the frontal plane like the hip abductors are known to have an important role as an antigravity muscle group and for maintaining balance during single leg stance phases in walking and standing (Winter, 1995). Previous research on non-amputee (nonAMP) sprinting has also shown that frontal plane hip and knee joint moments are smaller, but not negligible compared to those in the sagittal plane (Schache, Blanche, Dorn, Brown, Rosenmond & Pandy, 2011). However, the role of frontal plane mechanics and the magnitude of frontal plane joint loads during the long jump take-off step of nonAMP athletes is unknown.
One previous study analysed the take-off step kinetics of athletes with a below the knee amputation (BKA), and found that the center of mass (COM) mechanics and joint energy exchange are fundamentally different compared to those of nonAMP athletes (Willwacher et al. 2017). However, joint moments or movement plane specific joint energy exchange were not included in their work. A differentiated description of the musculo-skeletal loads during the long jump take-off step is missing for athletes with and without BKA. This information is important for understanding joint loading and injury mechanisms, and will help athletes, coaches and clinicians to improve training and rehabilitation protocols and prosthetic design.
The aim of this study therefore was to quantify and compare frontal plane take-off step mechanics of athletes with and without a BKA in athletic long jumping.

METHODS: Three long jumpers with BKA (mass: 78.7 ± 9.8 kg; height: 183 ± 4 cm; personal record [PR]: 7.43 ± 0.99 m) and seven nonAMP long jumpers (mass: 80.1 kg; height: 182 ± 7 cm; PR: 7.65 ± 0.65 m) voluntarily participated in the study. The prosthesis used by the athletes with BKA consisted of a custom-made and individually aligned socket and a carbon fiber running-specific prosthesis (RSP) (Össur, Iceland). All athletes with BKA used their affected side for the take-off step. After approaching with full effort from their typical competition run-up distance, all athletes performed three to six maximal-distance long jumps. The take-off step kinematic and kinetic data were captured using a three-dimensional motion capture system (VICON™, Oxford, UK) and a force plate (Kistler™, Winterthur, Switzerland) mounted flush with the floor. Retro-reflective markers were attached to anatomic reference points and on the prosthesis using double-sided tape. Kinematic and kinetic data were filtered (Butterworth, fourth order, 50 Hz cut-off, recursive) and time normalized to the stance time of the take-off step. Ground contact was identified using a 10 N threshold of the vertical ground reaction force (GRF). A modified mathematical rigid multibody system (Dynamicus, Alaska, The Institute of mechatronics, Chemnitz, Germany) was used for inverse dynamic model calculations (Fig1.A). The RSP of the athletes with BKA was modelled as a two-segment rigid body system connected by a ball and socket joint. Jump distance was calculated as the theoretical distance between the most anterior point of the foot/RSP during the take-off step and the intersection between the COM flight path and floor level. Only the best jump of each athlete was analysed. Further details on the model and calculation of jump distance are described in Willwacher et al. (2017). Medio-lateral COM displacement during stance was calculated in the global laboratory coordinate system as the distance of the respective COM coordinate to the COM coordinate at touch down (TD). In addition, the medio-lateral distance between the COM and the toe or RSP tip was calculated in order to get information on foot/RSP placement. Due to the small sample size a non-parametric Wilcoxon ranked sum test was used to identify differences between groups with a level of significance of 5%. Additionally, the percentage difference of the athletes with BKA relative to the nonAMP athletes was calculated.

RESULTS AND DISCUSSION: Theoretical jump distances were not different between athletes with BKA (7.26 ± 0.77 m) and the nonAMP athletes (7.27 ± 0.45 m). There was minimal medio-lateral GRF acting on the athletes with BKA, but a pronouced force peak in the lateral direction was found for the nonAMP athletes (Fig.1B). This might be explained by a different (p=0.017) medio-lateral foot position represented by the COM-Toe distance (Fig.1D) in the respective direction, which might have been induced and constrained by the mechanical rigidity of the RSP for athletes with a BKA. During ground contact, the COM of athletes with BKA was consistently about 6 cm medial to the foot. The COM of the nonAMP athletes, however, moved from 0.5 cm medial at TD to a position 3.4 cm lateral to the take-off foot at toe off (TO).

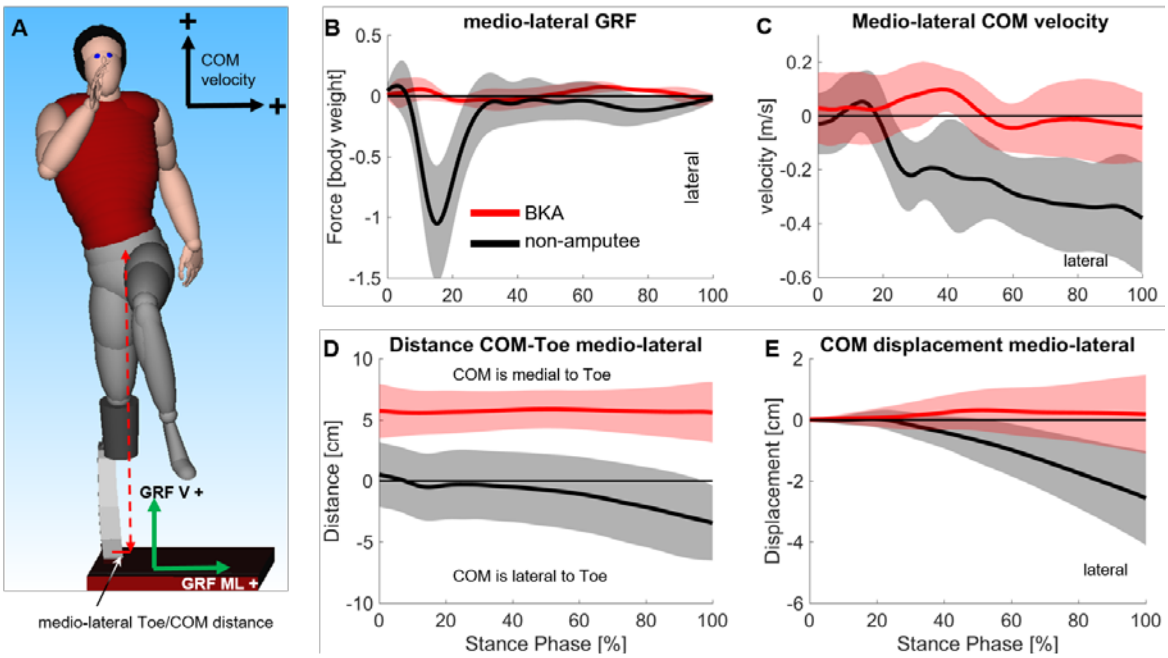

Figure 1: Left: Graphical representation of important measures and orientations of coordinate systems. Right: Medio-lateral ground reaction force (top left), medio-lateral center of mass (COM) velocity (top right), medio-lateral COM-Toe distance (bottom left), COM displacement during stance in the medio-lateral direction (bottom right). Mean values (solid lines) and standard deviation (shaded) for the athletes with BKA (red) and the non-amputee athletes (black).

From a COM mechanics perspective, avoiding braking or medio-lateral forces implicates a more efficient take-off technique and results in lower frontal plane joint loads (Fig. 2). Medio-lateral force production in sprint starts, however, was shown to not necessarily limit sagittal plane force application (Willwacher et al., 2016) but might provide the chance to increase total force output in the sagittal direction by including muscle groups mainly used in other planes of movement. If this is also true for the long jump, a limitation of muscle groups available for propulsion due to the unique specification of RSPs could induce a performance limitation onto those athletes who are using them. Whether the observed differences in medio-lateral GRF between athletes with BKA and nonAMP athletes are due to limited force production capacities or result from a fundamentaly altered take-off technique should be adressed in future studies on the long jump.

The nonAMP athletes showed an increasing velocity in lateral direction resulting in a distinct displacement in the same direction at TO of 2.6 cm (Fig.1E). Neglecting air resistance and using the aerial time of 0.884 s calculated by Willwacher et al. (2017) for the same data set, a take-off velocity in the lateral direction of 0.38 m/s (Fig.1C) would result in a COM displacement 34 cm in the lateral direction during the flight phase. However, using simple trigonometry and a jump distance of 7.26 m, this 34 cm of lateral displacement would increase the absolute linear distance jumped by only about 1 cm. NonAMP athletes' jump performance measured at competitions is therefore not relevantly affected by having a lateral take-off velocity.

The peak external knee adduction moments (Fig.2) of the nonAMP athletes were higher (~50%) than those reported for sprinting (Schache et al., 2011) and five to six times higher than those reported for stair climbing (Lin, Lu & Hsu, 2004). In athletes with BKA the knee joint loading shifted laterally (mostly abduction moment) compared to the loadings applied on the knee joints of the nonAMP athletes (mainly adduction moment) (Fig.2). This shift in joint loading can be partly explained by differences in the magnitude of the medio-lateral GRF affecting the resulting GRF vector orientation and is important information for clinicians to differentially diagnose knee pain or injuries. A high external knee adduction moment, as shown by the nonAMP athletes, is an accepted surrogate for an accelerated progression of medial gonarthritis (Miyazaki, Wada, Kawahara, Sato, Baba & Shimada, 2002), whereas a high external knee adduction impulse, has been associated with patellofemoral pain in runners (Stefanyshyn, Stergiou, Lun, Meeuwisse & Worobets 2006). The external knee abduction moment found in athletes with BKA during the take-off step (Fig.2) contrasts the adduction moments of people with a unilateral transtibial amputation during straight walking (Royer & Wasilewski, 2005). External abduction moments apply load on the lateral knee joint compartiment during the take-off step, which might stress structures that are not adequately adapted due to the missing stimulus from daily walking.

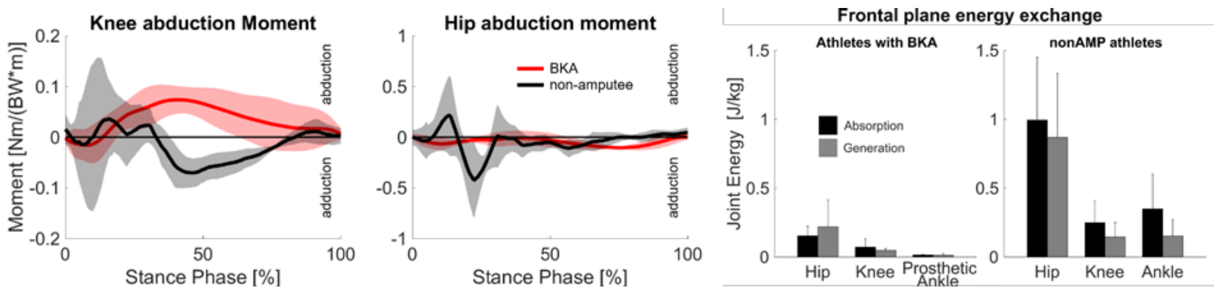

Figure 2: Left: External knee and hip abduction and adduction moments normalized to body weight and height. Mean values (solid lines) and standard deviation (shaded) for the athletes with BKA (red) and non-amputee athletes (black). Right: Frontal plane hip, knee and ankle energy absorption (black) and generation/return (grey) for the athletes with and without a BKA normalized to body mass.

The external peak hip adduction moments (Fig. 2) during the take-off step of nonAMP athletes were 2.7-fold higher compared to those in sprinting (Schache et al., 2011). This results in higher loads applied on the muscles resposible for hip abduction and underlines their important role in counteracting gravity and maintaining balance (Winter, 1995).

However, the above described role of the hip abductors seems to be more distinct in nonAMP athletes compared to athletes with BKA, as their peak frontal plane hip moments were 76% (abduction: p=0.017) and 87% (adduction: p=0.033) lower. Furthermore, in athletes with BKA there is minimal energy exchange in the frontal plane, whereas nonAMP athletes showed significantly different and moderately high absorption (0.99 J/kg, p=0.017) and generation/return (0.87 J/kg, p=0.017), especially in frontal plane hip joint energy exchange (Fig.2). Athletes, specifically nonAMP athletes, should be encouraged to strengthen the muscles surrounding the hip before practicing a full effort long jump take-off step due to the unique loads encountered.
Joint kinetics of athletes with a BKA remain unclear for sprinting and the long jump approach, especially in the frontal plane. Therefore, in order to determine the total musculo-skeletal load during the long jump in athletes with an amputation also the approach run should be analysed in future studies.

CONCLUSION: This study provides frontal plane mechanics for both athletes with and without a BKA during the long jump take-off step. Athletes with BKA showed different frontal plane kinematics and kinetics compared to nonAMP athletes. Medio-lateral GRF and frontal plane joint moments were lower for athletes with BKA compared to nonAMP athletes. Moreover, the long jump of athletes with BKA involves significantly less frontal plane joint work than nonAMP athletes. Athletes, specifically nonAMP athletes, should strengthen the muscles surrounding the hip before practicing a full effort long jump take-off step to avoid injuries early in the season. The presented findings should also enable coaches and clinicians to more differentially diagnose causes of pain or injuries in the hip and knee joint in both groups of athletes and adapt training and rehabilitation protocols accordingly.

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