LONG JUMP MECHANICS – OLYMPIC VERSUS PARALYMPIC CHAMPION

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In the last 20 years the long jump world record of athletes with an amputation of the lower extremities has improved by over two meters. However, there is no recent research on amputee long jumping and no information about amputee long jump kinetics. In this study the take-off step of an Olympic and a Paralympic champion were analyzed with regard to jumping mechanics. A 3D motion capturing system (Vicon) and a force plate (Kistler) were used to capture kinematic and kinetic data. Inverse dynamic calculations (Dynamicus, Alaska) revealed remarkable differences with respect to mechanical loading and motor solutions between the transtibial amputee and non-amputee long jumper. Mechanical constraints and material properties of the prosthesis might influence the kinematic chain of the amputee athlete and impose the need for an alternative motor solution.

KEYWORDS: GRF, athletics, kinetics, prosthetic design, amputee, joint moments

INTRODUCTION: Athletes with amputations are able to perform at a remarkably high performance level. The current world record (8.40 m) for athletes with a unilateral below the knee amputation (BKA) would have been sufficient to win the last three Olympic games. In competition, long jumpers with leg amputations use carbon fiber running-specific prostheses (RSPs). In order to understand the capabilities of RSPs, improve prosthetic design, and potentially improve the performance of athletes with BKA, it is important to determine the underlying biomechanics of amputee long jumping. Nolan et al. measured amputee long jumping kinematics during major competitions at the end of the last and beginning of the current century (Nolan et al., 2000, 2006, 2007, 2012). Since then the world record of athletes with BKA has improved by nearly two meters and athletes with unilateral BKA now primarily use their affected leg as their take-off leg.
Muraki et al. (2008) analyzed take-off mechanics including ground reaction forces (GRFs) and joint kinetics of eleven non-amputee athletes during full approach long jumping. Further, research on sprinting in athletes with bilateral BKA revealed differences with regard to joint mechanics and ground reaction forces between amputee and non-amputee athletes (Brüggemann et at., 2008; Weyand et al., 2009). There is no research on elite long jump kinetics of athletes with BKA. Knowledge about loading applied on the prosthesis and the musculoskeletal system of the athletes with BKA is important for the design process of future prosthesis generations. Moreover, coaches and athletes would benefit from a kinematic and kinetic analysis, which could result in the development of specific training protocols.
Thus, the purpose of this study was to analyze and compare the joint-level kinematics and kinetics during the take-off step of the long jump in elite athletes with and without BKA.

METHODS: Two of the best long jumpers in the world, one with BKA (AMP) and one without BKA (nonAMP), participated in this study (Table 1). The prosthesis used by AMP consisted of a custom-made and individually aligned shaft and a carbon fiber RSP (Össur, Iceland). Both athletes performed maximal-distance long jumps using their typical competition run-up distance. For the take-off step, kinematic data were captured using a 3D motion capture system (VICON™, Oxford, UK) and kinetic data were captured with a force plate (Kistler™, Winterthur, Switzerland) mounted flush to the floor. Retro-reflective markers were placed on anatomic reference points and on the prosthesis.

Table 1
Subject details including anthropometrics and personal best (PB).

Subject	PB [m]	Mass [kg]	Height [m]
AMP	8.40	76.2	1.84
nonAMP	8.52	86.9	1.79

A mathematical rigid multibody system (Dynamicus, Alaska, The Institute of mechatronics, Chemnitz, Germany) was used for inverse dynamic calculations. The carbon-fibre blade of the RSP was reconstructed as a two-segment rigid body system. The prosthetic “ankle joint” was defined by two markers at the medial and lateral edge of the blade located at the point of its greatest curvature. Kinematic and kinetic data were filtered by a 4^{th} order recursive butterworth filter with a 50 Hz cutoff frequency. All data were time normalized to the duration of the stance phase of the take-off step. Ground contact was determined using a 20 N threshold in vertical ground reaction force. Only the best jump of each athlete was analyzed. For this reason, no statistical analyses was performed and thus the reported results are a qualitative indication of the underlying biomechanics.

RESULTS AND DISCUSSION: GRFs are clearly different between nonAMP and AMP (Table 2, Figure 1). The peak horizontal braking force is approximately three times greater in magnitude for the nonAMP. Whereas the medio-lateral force is negligible for AMP, nonAMP has a larger peak in the medial direction during the first 30% of the stance phase.

Table 2
Peak ground reaction forces, joint moments, joint work and joint angles for the athlete with BKA (AMP) and the non-amputee athlete (nonAMP).

		AMP	**nonAMP**
Peak Ground Reaction Force [N/kg]			
	Braking	18.54	59.72
	Propulsive	6.35	3.19
	Medial	0.85	0.92
	Lateral	1.27	18.56
	Vertical	62.28	120.13
Peak Joint Moments [Nm/kg]			
Ankle/Prosthesis	flexion	9.06	2.22
	extension	--	1.02
Knee	flexion	1.87	5.08
	extension	0.95	0.97
Hip	flexion	1.93	8.72
	extension	1.40	5.68
Joint Work [Nm/kg]			
Ankle/Prosthesis	absorped	5.67	0.87
	generated	4.39	1.52
Knee	absorped	0.90	4.62
	generated	0.19	1.78
Hip	absorped	0.05	1.40
	generated	1.14	1.42
Peak Joint Angles [°]			
Ankle/Prosthesis	flexion	30.6	13.9
	extension	--	30.2
Knee	flexion	28.2	51.6
	extension	3.0	0.76
Hip	flexion	14.6	38.1
	extension	25.1	25.2

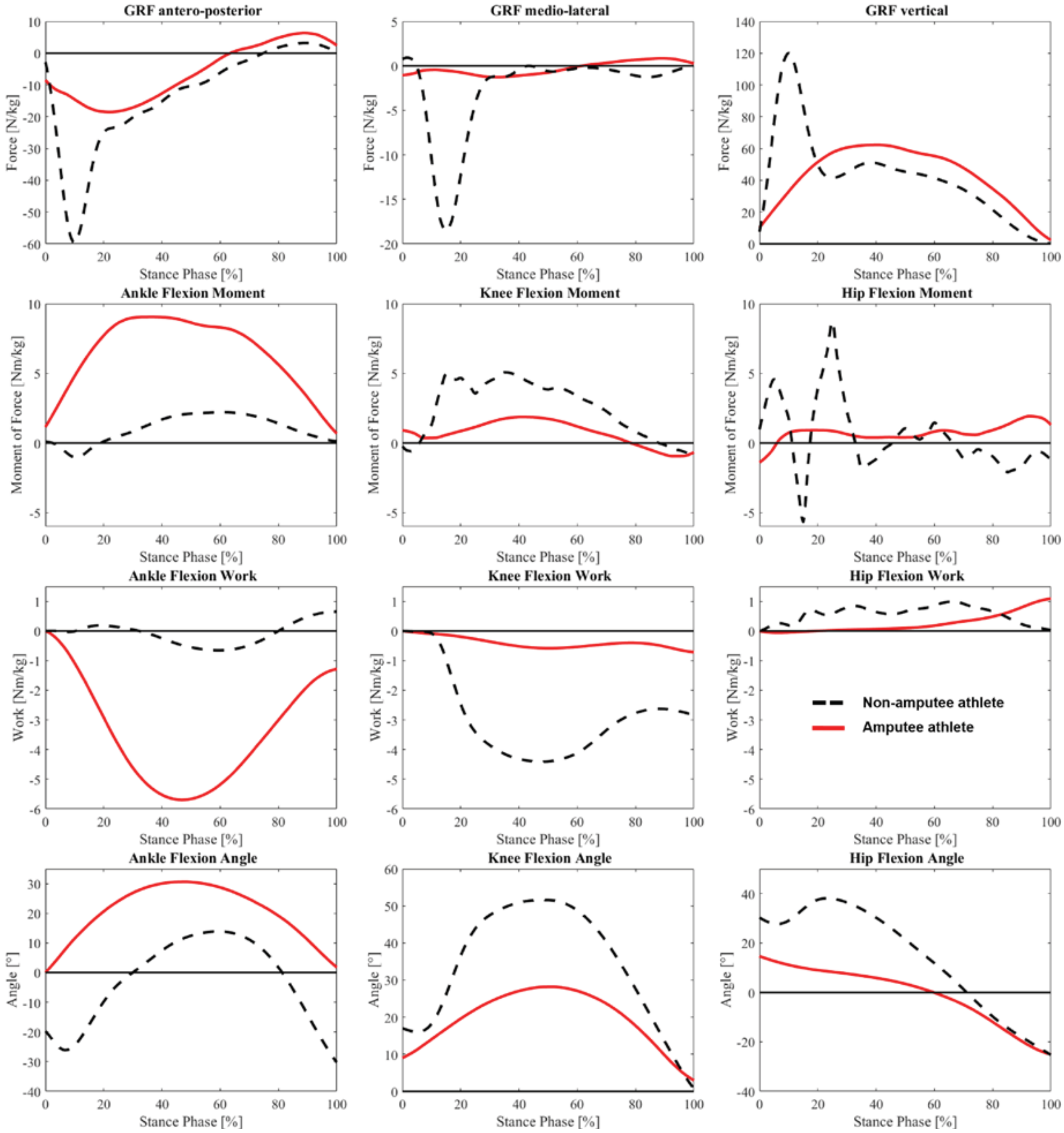

Figure 1: Ground reaction forces (top row), joint moments (second row), joint work (third row) and joint angles (bottom row) for the non-amputee athlete (black dashed) and the amputee athlete (red solid). All graphs are time normalized to ground contact of the take-off step and kinetic parameters are normalized body mass. Joint moments represent external joint moments.

The vertical GRF of AMP is similar to a half-sinus wave from a spring-mass model (Seyfarth et al., 1999). NonAMP however shows a pronounced peak during the first 20% of the stance phase exceeding the vertical GRF peak of AMP by a factor of two. After this first peak, the vertical GRF of nonAMP remains lower compared to AMP. These vertical GRF data of nonAMP are comparable to those reported by Muraki et al. (2008).
Due to a longer lever arm between the resultant GRF and prosthetic ankle compared to that between the resultant GRF and the biological ankle, the peak ankle flexion moment of AMP is about four times higher than that of the nonAMP. The knee flexion moment, however, is by a factor two higher for nonAMP. Amplitude and shape of nonAMP's sagittal plane joint moments match those reported by Muraki et al. (2008). Comparing sagittal plane joint moments of the prosthetic ankle to the biological ankle from a performance perspective is

difficult and conclusions should be drawn carefully, but still it provides valuable information for design and material properties of future prostheses.
Greater mechanical energy is absorbed and generated in the prosthetic ankle joint compared to the biological ankle joint. However, the net mechanical energy is negative for AMP and positive for nonAMP. At the knee joint, more energy is absorbed and generated by nonAMP compared to AMP. The net mechanical energy at this joint is negative for both athletes. Compared to the ankle and knee joint, the mechanical work of the hip joint is lower for both athletes. However, AMP takes off with a slightly positive net mechanical energy at the hip joint whereas energy absorption and generation of nonAMP is very balanced at the hip joint. Focusing on the sagittal plane only, it appears that the proportion of total energy absorption to energy generation is more balanced for AMP than for nonAMP.
Sagittal joint angles show a greater range of motion (RoM) for nonAMP compared to AMP in all three major joints of the lower extremities. Due to the mechanical constraints of the RSP, there is flexion but no extension movement. The biological ankle joint of nonAMP, in contrast, only flexes during mid-stance (30 – 80%). NonAMP has a more flexed hip at touch down compared to AMP and flexes his hip even more in the first 20% of the stance phase. In contrast to that, AMP shows a pure extension movement of the hip during the stance phase. Mechanical and material properties of the prosthesis are constraintsthat seem to influence the kinematic chain of the amputee athlete. The necessity to vary kinematics might lead to different requirements of motor control and could be of interest in future research.

CONCLUSION: Mechanical loading and motor solutions show remarkable differences between elite long jumpers with and without a transtibial amputation. Mechanical constraints of the running-specific prosthesis used by the athlete with an amputation might influence the kinematic chain of this athlete and impose the need of an alternative motor solution. This is important information for coaches and athletes as they might have to focus on different aspects of each athlete's movement and cannot simply transfer strategies used for non-amputee performance diagnostics. Moreover this study gives initial insight to the loads applied on the musculoskeletal system and the prosthesis of an athlete with unilateral below the knee amputation. This is valuable information for both injury prevention and the design process of future prostheses generations. However, this study only analyzed the kinematics and kinetics of two athletes, who are both at an elite performance level for human long jumping and therefore more comprehensive research is needed to generalize these findings.

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