THE USE OF UPPER LIMB PROSTHESIS OPTIMIZES LONG JUMP APPROACH KINEMATICS: A CASE STUDY OF AN ELITE T47 ATHLETE

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This study aimed to investigate approach run kinematics using an upper limb prosthesis. A European T47 long- and triple- jump champion with right upper-limb congenital deficiency was analyzed in simulated approach run-ups wearing prosthesis (PW) or not (NP). Two attempts in each condition were recorded (300 fps). Step characteristics and kinematic parameters were extracted for the deficient (DLS) and intact (HLS) sides with a 2D-DLT analysis during the early (EA) and late (LA) approach. Results revealed systematic asymmetry for step frequency and length in NP, with the latter reduced in PW. Horizontal velocity in both EA and LA was larger by 0.3 m/s in PW than NP. These results suggest that asymmetry of NP reduces approach run performance compared to PW.

KEYWORDS: prosthetics, Paralympics, biomechanical analysis, angular momentum.

INTRODUCTION: The increasing number of amputees participating in and greater spectator numbers attending Paralympic sports events have increased interest in Paralympic sports performance. Nevertheless, limited scientific data is available on sport prostheses and prosthetic adaptations (Bragaru et al., 2012).
Previous studies have biomechanically analyzed jumpers with transtibial and transfemoral amputation in elite level competition (Nolan & Lees, 2007; Padulles et al., 2019); however there is little information concerning upper arm amputee long jumpers. Upper arm amputees compete as T45, T46 and T47. According to the International Paralympic Committee (IPC), participants in T47 class are "*athletes with a unilateral upper limb impairment resulting in some loss of function at the shoulder, elbow and wrist and which impacts sprints primarily, where the impact of the impairment is comparable to the activity limitations experienced by an athlete with a unilateral through wrist/below elbow amputation*". Paralympic T47 athletes may choose whether or not to wear upper limb prostheses during competition. However, wearing prostheses and an increased forearm mass has been suggested to improve long jump performance as horizontal velocity was increased (Pradon et al., 2014). Greater between-leg asymmetry was found for average sprinting vertical support forces in lower limb amputees compared to non-amputee long jumpers (Willwacher et al., 2017), but limited information is available regarding the effect of wearing or not prostheses on asymmetry regarding approach step parameters for upper limb amputees.
The aim of this study was to investigate biomechanical differences in long jump approach run-up when performing with and without upper limb prosthesis. It was hypothesised that asymmetry would increase in the approach step characteristics and the joint angular kinematics of the sprinting technique during the run-up when not wearing the prosthesis.

METHODS: The 2016 IPC Athletics European T47 long jump champion and 2017 IPC World Championship T47 triple jump silver medalist (age: 25 yrs; body height: 1.77 m; body mass: 65 kg) was examined in the present case study. The participant had a right upper limb congenital deficiency and wore a transradial prosthesis in athletics competitions. The study was conducted after obtaining signed consent in accordance to the ethical approval obtained from the Institutional Bio-Ethics Committee (1010/26-04-17).

The participant performed simulated run-throughs of the approach run during a training session in two conditions: wearing the prosthesis (PW) or without prosthesis (NP). Two attempts in each condition were recorded with three digital video cameras (Casio EX-FX1, Casio Computer, Shibuya, Japan) operating at 300 fps. A 6-minute interval was allowed between run-ups. A panned video camera was used to record the approach (APP) step parameters. The panning camera was positioned 20 m from the midline of the run-up lane, 8 m before the take-off board and at a height of 3 m from ground level. The camera was manually panned and zoomed on the participant for the last 20 m of the run-up. For the extraction of step parameters, 0.05 m × 0.05 m custom reference markers were placed on either side of the lines defining the runway at 1 m intervals. Calibration and the panning procedure were conducted according to the guidelines proposed by Gervais et al. (1989). The frames depicting each support phase of the approach were inserted to the APAS WIZARD v. 13.3.0.3 software (Ariel Dynamics, Trabuco Canyon, CA, USA). Step length (SL), frequency (SF) and average velocity (ASV) was calculated according to Theodorou *et al.* (2016). The last 11 steps of the approach were selected for further analysis. Step characteristic asymmetry was calculated based on the method of Exell et al. (2012). Asymmetry magnitude was quantified between steps from the ispilateral leg (HLS) and contralateral leg to the deficient upper arm (DLS) using the symmetry angle (θ_{SYM}) equation:

$$\theta_{SYM} = (45 - \text{atan}\ (X_{DLS} / X_{HLS})) / 90)\ X\ 100$$

where X_{HLS} and X_{DLS} = mean HLS and DLS limb values, respectively, with HLS being the take-off leg. Following tests for normality (Shapiro-Wilk), Mann-Whitney U tests between sides for each step characteristic determined whether asymmetry was significant ($p < 0.05$) with respect to intra-limb variability for the step characteristic measures (Exell et al., 2012).

The two stationary cameras recorded early (EA) and late (LA) approach kinematic parameters. The cameras were positioned 12 m from the middle of the runway and at a distance of 14 m and 6 m from the take-off board for EA and LA, respectively. Calibration was conducted by placing a 2.5 m x 2.5 m frame with 16 control markers perpendicular to the cameras' axis. The X-axis represented the direction of the runway and Y-axis was vertical and perpendicular to the X-axis. Eighteen anatomical points of the body were manually digitized in each recorded video field. The coordinates of the body center of mass (BCM) were calculated for every field using anatomical data provided by Dempster (1955) and prosthesis center of mass characteristics that were measured using the method described by Clauser et al. (1963). A second-order low-pass Butterworth filter (cut-off frequency: 6 Hz) was selected for smoothing. BCM horizontal (Vx_{BCM}) and vertical (Vy_{BCM}) velocity, along with shoulder range of motion (ROM_{SH}) and the maximum hip, knee and ankle (ω_{HIP}, ω_{KNEE} and ω_{ANK}, respectively) extension angular velocities, were extracted for HLS and DLS with a 2D-DLT analysis method using the KAPA-MOTION v.15 software (K-Invent, Orsay, France). The angular momentum of the whole body (Hx_{BCM}) about the transverse axis at EA and LA was calculated according to Robertson et al. (2014), using inverse dynamics analysis and segmental moments of inertia proposed by Witsett (1963). Descriptive statistics were used for the identification of differences between EA and LA and DLS and HLS.

RESULTS: Systematic asymmetry was revealed for SF and SL in NP, with the latter reduced in PW (Table 1). In the entire approach, the step initiated by DLS was 6.1% longer, had 4.6% lower SF and was on average 1.8% faster in NP. A smaller difference between SL in HLS and DLS (4.9%), with non-significant asymmetry, was observed in PW. Findings concerning SF in PW were the same as NP. Finally, ASV difference between DLS and HLS was reduced to 0.5%.

Vx_{BCM} in both EA and LA was larger in PW than NP (Table 2). DLS ROM_{SH} was lower in PW than NP. At LA, ω_{ANK} was higher in NP than PW for both DLS and HLS. ω_{KNEE} of HLS was also larger for both PW and NP conditions, especially at LA. Hx_{BCM} was larger in all HLS and also in all PW conditions with the exception of HLS at LA (Figure 1). Finally, DLS arm had a smaller contribution to Hx_{BCM} in NP than PW.

Table 1: Mean step characteristics and symmetry angle results (θ_{SYM}) in PW and NP conditions.

Parameter	Step Length (m)			Step Frequency (Hz)			Step Velocity (m/s)		
	DLS	HLS	θ_{SYM}	DLS	HLS	θ_{SYM}	DLS	HLS	θ_{SYM}
NP	2.20	2.06	-2.09*	4.25	4.45	1.46*	9.34	9.19	-0.52
PW	2.20	2.09	-1.63	4.25	4.45	1.46*	9.36	9.31	-0.17

** = significant asymmetry (p<0.05)*

Table 2: Kinematics and symmetry angle results in PW and NP for EA and LA (mean ± SD).

Approach phase:	EA		LA	
Condition:	NP	PW	NP	PW
Vx_{BCM} (m/s)	9.5 ± 0.1	9.8 ± 0.1	9.8 ± 0.1	10.0 ± 0.2
Vy_{BCM} (m/s)	0.3 ± 0.1	0.4 ± 0.0	0.5 ± 0.1	0.6 ± 0.2
DLS ROM_{SH} (deg)	57.2 ± 0.6	38.2 ± 3.1	51.2 ± 11.8	39.4 ± 2.2
DLS ω_{HIP} (rad/s)	13.2 ± 0.3	12.7 ± 1.2	12.6 ± 1.2	12.7 ± 0.6
HLS ω_{HIP} (rad/s)	12.1 ± 1.2	13.3 ± 0.5	13.7 ± 0.8	13.5 ± 0.6
DLS ω_{KNEE} (rad/s)	3.2 ± 0.8	2.9 ± 0.6	3.8 ± 1.9	3.9 ± 0.7
HLS ω_{KNEE} (rad/s)	3.9 ± 1.6	4.0 ± 0.9	5.8 ± 0.3	5.0 ± 0.9
DLS ω_{ANK} (rad/s)	13.6 ± 0.3	14.4 ± 0.1	15.4 ± 0.6	13.3 ± 0.2
HLS ω_{ANK} (rad/s)	13.7 ± 2.2	11.9 ± 1.0	15.3 ± 2.0	14.4 ± 0.4

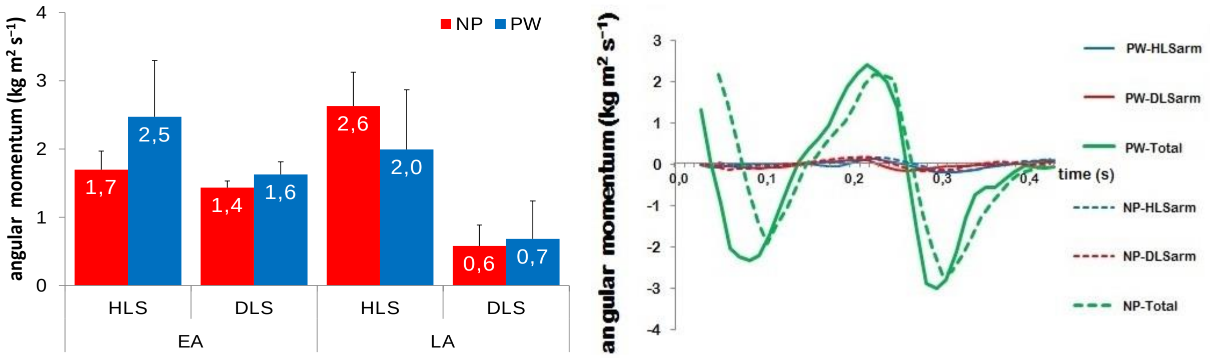

Figure 1: Average total body angular momentum for PW and NP at EA and LA (left) and representational upper limbs' segmental angular momentum at LA (right). Graphs depict the mediolateral component of angular momentum.

DISCUSSION: The aim of this study was to investigate biomechanical differences in long jump approach run when performed with and without an upper limb prosthesis. Asymmetry in step frequency and length has been previously reported in long jump approach for non-amputee athletes (Theodorou et al., 2016). However, despite the asymmetrical explosive movement of the take-off, few occurrences of significant asymmetry for step parameters were observed in long jumpers. In the present study, significant asymmetry of similar magnitude to that previously reported in able-bodied athletes (Theodorou et al., 2016) was observed for step frequency and step length when the run-ups were executed without the prosthesis. However, the prosthesis allowed the participant to reduce asymmetry in SL and SV between steps initiated from HLS and DLS in comparison to the run-ups without the prosthesis. The reduced asymmetry when running with the prosthesis can be attributed to the increased moment of inertia around the shoulder. When the participant was not wearing the prosthesis, the reduced angular momentum generated by the upper limb was compensated with increased range of motion at the shoulder. Previous research has reported higher swing velocity for the deficient arm in upper limb amputees (Mally et al., 2015). In the present study, PW led to smaller shoulder range of motion than NP, lower angular momentum at HLS compared to DLS step take-off in LA and to lateral differences of the lower limb extension angular velocities during EA. This finding suggests that PW assisted to the cancelation of angular momentum due to the forward and backward arm swing, which is desirable for the entire body during running (Hinrichs, 1987).

Larger upper limb prosthetic mass has shown to increase the ability of the athlete to transform the horizontal velocity of the BCM to vertical velocity but without improvements in long jump performance (Pradon et al., 2014). However, it is unclear if upper limb prostheses improve (Panoutsakopoulos et al., 2016) long jump performance or not (Jones, 2016). None of the above studies investigated possible asymmetry in step parameters. Thus, the influence of the upper limb prosthesis on step characteristic asymmetry is a new finding and highlights the importance of studying amputee long jump performance in the future. In addition, it has been suggested that upper limb prosthesis may create advantages concerning the effectiveness of ankle joint torque and power generation at the take-off phase for the long jump (Jones, 2016). Taking this finding into account, future research should also study the modifications in the biomechanics of the lower limbs' sprinting actions for the execution of the long jump approach run due to the use of a prosthetic forearm.

CONCLUSION: The use of the upper limb prosthesis improved the execution of the approach run, as less step parameters' asymmetry and a more efficient sprinting technique were observed. When wearing the transradial prosthesis, the participant seemed to optimize the total body angular momentum that led to less asymmetrical approach run and thus to higher approach velocity, which may eventually improve long jump performance.

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