MECHANICS OF AMPUTEE JUMPING – CONSIDERATION FOR LOADING

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Amputees must develop compensatory mechanisms to overcome the constraints imposed by a mechanical prosthesis. In completing a bilateral countermovement jump, amputees must accommodate the limited ankle dorsiflexion angle and adapt to the limited plantar-flexor moment that occurs at the prosthetic joint. The aim of this research was to determine the loading on the limbs and the joint kinetics adopted by transtibial amputees in order to achieve a jump. Six amputee (AMP) and 10 able-bodied (AB) participants performed maximal vertical jumps on two force plates while kinematic data was recorded using a 9-camera VICON infrared system. The amputees did not jump as high as the AB participants. The AMPs raised the prosthetic heel from the floor to compensate for the restricted motion at the ankle. Consequently, kinematic symmetry was maintained at the knee and the hip. The knee flexion places the prosthetic shank in a more horizontal position. This is a vulnerable position due to the reduced strength in the knee extensors as a consequence of the amputation. In order to reduce the instability and loading at the knee, the maximum propulsive vGRF on the prosthetic side was reduced and the intact limb assumed a dominant role. Until amputees can take the loading on the prosthetic side, it is not recommended that they participate in jumping.

KEY WORDS: loading, jump, amputee.

INTRODUCTION: A below-knee amputation causes a major disruption to the musculoskeletal system. Prosthetic design has attempted to reduce the consequences of the amputation by developing dynamic elastic response (DER) prostheses. The aim of these devices is to absorb strain energy when a load is applied and then to return this energy as elastic energy when the prosthesis is unloaded. However, because the prostheses are passive, they are not capable of replacing the adaptable function of the intact limb. As a result compensatory mechanisms develop in the residual limb and in the intact limb. Asymmetry in amputee biomechanics have been reported in various walking and running studies usually to maintain the prosthetic limb in an upright position and to ensure stability at the knee (Nolan et al., 2003; Sanderson and Martin, 1997). Vertical ground reaction force (vGRF) analyses indicate that the intact limb generally adopts a dominant role in gait with increased vGRF loading when compared to the prosthetic limb and other able bodied participants. It is suggested that Amputees load the intact side to protect the residual limb (Nolan et al., 2003). Possibly as a consequence of this asymmetrical loading, amputees evidence greater joint degeneration in their intact limb compared to both the residual limb and able bodied (AB) subjects. Melzer et al., (2001), reported that both highly active amputees and those who are not active had a 65.5% greater incidence of osteoarthritis (OA) in their intact limb compared to AB equivalents. Walking and running gait are unilateral movements which have different mechanics to the bilateral contermovement jump (CMJ) which requires simultaneous contribution from both limbs to generate the required forces to achieve flight. The aim of this study was to determine the levels of loading and joint kinetics required by amputees to produce a bilateral CMJ.

METHODS: Participants: Six unilateral transtibial AMPs (5 males and 1 female) who were between 18 and 50 years, more than 12 months post-operative, with no secondary pathology and had an amputation of a traumatic nature were recruited. All the AMPs wore patellar tendon-bearing sockets with rigid pylons and their own prosthesis. Ten AB participants (9 male and 1 female) of the same age range with no pathology were used to facilitate the comparison of results. All participants (AMPs and AB) were recreationally active with similar proficiency in jumping and wore their own footwear (athletic trainers). All participants signed an informed consent form approved by the University and the National Health Services' Ethics Committee.

Data Collection: Data were collected in a single session. Following a 5 minute warm-up on a treadmill at a self-selected fast walking velocity, participants were given the opportunity to practise the movement and become familiar with the laboratory setting. Ten maximum effort bilateral countermovement jumps (CMJ) were performed with hands on hips with 1 minute rest between each trial. The only instruction given was to jump as high as possible. The jumps were performed with each foot on a separate force plate. Trials were excluded if the participants used their arms or if they missed the force plate during landing. On average 13 jumps were required to collect 10 successful trials. Data were collected using two Kistler (model 9581B, sampling at 1080Hz) force plates synchronized with a 9-camera Vicon (model 612, sampling at 120Hz) infra red system. Thirty four 25mm diameter reflective markers were attached to specific anatomical landmarks according to Vicon's Plug-in-Gait full body gait model (Oxford Metrics). Measurements were taken for each individual according to the Vicon requirements for full body modelling.

Data Analysis: The jump with the highest flight height determined by the CoM displacement (maximum height less height at take-off) was chosen for analysis. Jump kinetics and kinematics were calculated with Vicon Workstation software. Kinematic data were filtered using a Woltering quintic spline (MSE = 15mm) filter. Inverse dynamics using standard procedures determined the net joint reaction components and the net joint moments (normalised to body mass) at the ankle, knee and hip from the ground reaction force data associated with each foot. All other variables are presented for the AMPs as intact and prosthetic limb separately. For the AB, the results are for the preferred and non-preferred jumping limb. The symmetry index (SI) was calculated $SI = \frac{(X_r - X_l)}{0.5(X_r + X_l)} * 100\%$

Where X_r is the variable for the right limb, and X_l is the corresponding variable for the left limb. The magnitude of the SI indicates the degree of symmetry and the sign indicates the direction (positive is greater on the intact side). A value of zero indicated perfect symmetry.

RESULTS: The flight height and maximum vertical ground reaction force for each limb is presented in Table 1. SI results outside one SD of the AB participants SI are indicated in bold.

Table 1 Flight height and maximum vGRF experienced by the AMPs and AB participants

	Flight Height (m)	*Max vGRF during propulsion (N.kg^{-1})*		
		Intact	Prosthetic	SI
AMP1	0.24	1.141	1.010	12
AMP2	0.19	1.182	0.971	**19**
AMP3	0.17	1.292	0.591	**75**
AMP4	0.13	1.228	0.861	**35**
AMP5	0.10	1.177	0.731	**47**
AMP6	0.09	1.178	0.844	**33**
$\bar{x}_{(AMP)}$ (± sd)	0.15 ±0.06	0.20 ±0.05	0.83 ±0.16	37 ±22
$\bar{x}_{(AB)}$ (± sd)	0.31±0.04	1.134±0.15	1.093±0.12	3±6

AMPs jumped lower than the AB participants. Each AMP loaded the intact limb more than the prosthetic limb. The magnitude of the loading on the intact limb was similar to the loading for the AB group, preferred limb. The two AMPs who jumped the highest experienced loading on the prosthetic limb that was similar to the AB group non-preferred limb loading.

Table 2 Heel rise and maximum flexion experienced by the AMPs and AB participants

	Heel Rise (m)	Ankle Angle (°)			Knee Angle (°)			Hip Angle (°)		
		Intact	Prosthetic	SI	Intact	Prosthetic	SI	Intact	Prosthetic	SI
AMP_1	0.07	44	16	34	91	100	-9	105	116	-10
AMP_2	0.06	38	19	22	94	89	5	87	95	-9
AMP_3	0.07	33	6	21	89	93	-4	85	96	**-12**
AMP_4	0.05	41	17	28	84	90	-7	91	104	**-13**
AMP_5	0.09	43	13	34	93	107	**-14**	92	101	**-9**
AMP_6	0.06	26	12	11	74	65	**13**	92	89	**3**
$\bar{x}$ (AMP) (sd)	0.07	38±7	14±5	25±9	88±8	91±14	-3±9	92±7	100±9	-8±6
$\bar{x}$ (AB) (sd)	0.03±0.02	39±5	37±8	2±6	111±12	111±12	0±12	94±10	95±13	1±11

The mechanical restraints of the prosthesis prevented adequate ankle dorsiflexion in the eccentric phase. To maintain symmetry at the knee and hip, the prosthetic heel rose from the floor. Negative SI indicates more flexion on the prosthetic side.

Table 3 Maximum joint moments experienced by the AMPs and AB participants

	Ankle Moment ($Nm.kg^{-1}$)			Knee Moment ($Nm.kg^{-1}$)			Hip Moment ($Nm.kg^{-1}$)		
	Intact	Prosthetic	SI	Intact	Prosthetic	SI	Intact	Prosthetic	SI
AMP_1	1.86	1.28	**37**	1.08	1.18	-9	2.45	2.55	**-4**
AMP_2	1.57	1.08	**37**	1.37	2.16	**-45**	1.67	2.16	**-26**
AMP_3	1.96	0.78	**86**	1.08	0.39	**94**	2.06	1.08	**62**
AMP_4	1.77	0.88	**67**	1.57	1.18	**28**	1.47	1.47	0
AMP_5	1.57	1.08	**37**	1.28	0.98	**27**	2.55	1.47	**54**
AMP_6	1.86	1.08	**53**	1.08	0.69	**44**	1.28	1.28	0
$\bar{x}$ (AMP) (sd)	1.8±0.2	1±0.2	52.8	1.2±0.2	1.1±0.6	23.2	1.9±0.5	1.7±0.6	14.3
$\bar{x}$ (AB) (sd)	1.57±0.2	1.47±0.2	7±0.2	1.57±0.3	1.57±0.3	0±0.3	1.77±0.5	1.86±0.06	-5±0

The ankle moments were asymmetrical and always smaller on the prosthetic side. At the intact knee the moments for the AMPs who jumped the highest were less on the intact side, while for the rest, the intact knee moments were greater. Overall, there was no clear trend for each joint related to height. The AMP joint moments were generally similar or lower at the ankles and knees but were similar at the hip compared to the AB participants.

DISCUSSION: Vertical jumping is a fundamental skill common to numerous recreational activities and training strategies. As jumping is a multi-joint action that requires substantial muscular effort about the ankle, knee and hip joints, it was expected that biomechanical compensations would result from the amputation. The results can be used to develop prosthetic design, to enhance rehabilitation and to develop exercise programmes for amputees for movements which require different loading and alternative movement patterns to walking.

The prosthetic ankle and the compensatory motor pattern adopted by these AMPs did not overcome the muscular and sensory loss of the anatomical limb. The AMPs did not achieve flight heights equivalent to the AB participants. In bilateral jumping kinematic asymmetry is restricted compared to walking and running due to the side-by-side positioning of the feet and the constraint of the pelvis. In order to produce a countermovement, dorsiflexion of the ankle and flexion of the knees and hips are required. As the AMPs were restricted in the magnitude of dorsiflexion, the heel rose to allow flexion at the knee and hip to occur. The resulting more horizontal positioning of the shank is usually avoided by AMPs who prefer a straight knee to maintain an upright prosthesis in walking (Barr et al., 1992), running (Sanderson and Martin, 1996), stair descent (Jones et al., 2006). In a unilateral jump, where AMPs cannot compensate at the contralateral limb, relatively straight knees were maintained, indicating this reluctance to flex the knee joint under loading (Strike and Diss, 2005). In the bilateral jump the intact limb can dominate. Although the prosthetic side knee flexed, the loading on the limb was reduced to prevent it collapsing (due to its reduced strength as a consequence of the amputation) and to stop excessive loading on it in this position. A consequence of this reduced loading was a smaller plantarflexor moment at the prosthetic ankle in the concentric phase, since, as a passive device, the moment is related to the loading on the prosthesis. This prosthetic plantarflexor moment was similar to the results often seen in gait, and indicates the limitation of the prosthesis to adapt to different demands, as would be expected from a passive, but responsive device. On the intact side, the reduced knee extensor moment could be as a result of a modulation to match the prosthetic limb to reduce asymmetry (Sanderson and Martin, 1996) or it could be to avoid loading the knee. Royer and Koenig (2005) illustrated the link between the increased frontal plane joint moments and bone mineral density in transtibial amputees when walking and suggested that the potential exists for premature intact-side knee joint degeneration in transtibial amputees.

CONCLUSION: AMPs did not jump as high as AB participants. The loading, as represented by the vGRF was lower on the prosthetic side and indicates that the intact side assumes a dominant role in producing the jump. These results imply that the AMPs were both promoting residual knee stability and protecting the residual joints by not loading the affected side. If amputees are to actively use the prosthetic limb when jumping, they need to learn to maintain knee stability in order to load the prosthesis. Until amputees can achieve this, it is not recommended that they participate in activities which excessively load the affected side with the knee in a flexed position. The contralateral loading may have consequences for the intact limb health given that amputtees hare known to have increased levels of OA on this side.

REFERENCES:

Barr, A., Siegel, K., Danoff, J., McGarvey, C., 3rd, Tomasko, A., Sable, I., et al. (1992). Biomechanical comparison of the energy-storing capabilities of SACH and Carbon Copy II prosthetic feet during the stance phase of gait in a person with below-knee amputation. *PHYS THER, 72*, 344-354.

Jones, S. F., Twigg, P. C., Scally, A. J., and Buckley, J. G. (2006). The mechanics of landing when stepping down in unilateral lower-limb amputees. *Clinical Biomechanics*, 21, 184-193.

Melzer, I., Yekutiel, M., and Sukenik, S. (2001). Comparative study of osteoarthritis of the contralateral knee joint of male amputees who do and do not play volleyball. *The Journal of Rheumatology*, 28, 169-172.

Nolan, L., Wit, A., Dudziñski, K., Lees, A., Lake, M., and Wychowañski, M. (2003). Adjustments in gait symmetry with walking speed in trans-femoral and trans-tibial amputees. *Gait and Posture*, 17, 142-151.

Royer, T., and Koenig, M. (2005). Joint loading and bone mineral density in persons with unilateral, trans-tibial amputation. *Clinical Biomechanics*, 20, 1119-1125.

Sanderson, D. J., and Martin, P. E. (1996). Joint kinetics in unilateral below-knee amputee patients during running,. *Archives of Physical Medicine and Rehabilitation*, 77, 1279-1285.

Sanderson, D. J., and Martin, P. E. (1997). Lower extremity kinematic and kinetic adaptations in unilateral below-knee amputees during walking. *Gait and Posture*, 6, 126-136.

Strike, S., and Diss, C. (2005). The biomechanics of one-footed vertical jump performance in unilateral transtibial amputees. *Prosthetics and Orthotics International*, 29, 39-51.