MECHANICS OF AMPUTEE JUMPING – JOINT WORK

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The purpose of this study was determine if dynamic elastic response (DER) prostheses could absorb energy in the eccentric phase of a vertical jump performed by trans-tibial amputees phase and return this energy in the propulsive phase. Further, given the active nature of the ankle, the study aimed to determine the mechanisms required at the remaining joints to compensate for the pathological ankle. Six amputee (AMP) and 10 able-bodied participants (AB) performed maximal vertical jumps on two force plates which were synchronised with a 9-camera VICON infra red system. The amputees did not jump as high as the AB participants. Only minimal negative work was recorded at the prosthetic ankle in the eccentric phase which resulted in minimal positive work at the ankle in the concentric phase. The intact side produced greater work than the affected side in the concentric phase. The amputees generally adopted a hip strategy to generate positive work. The work recorded at the knee was reduced on the intact and affected side and indicates the prosthesis influences the movement on both sides. To enable amputees to participate in activities which require jumping, prostheses need to be developed and amputees need to be taught how to adjust their biomechanics to store and release energy in the prosthesis.

KEY WORDS: amputee, vertical, jump, joint work.

INTRODUCTION:

Vertical jumping is a skill required for many sports. It is frequently used to assess explosive strength and as a field test of performance capability. There is little research on amputee bilateral vertical jumping and on the compensations that result from amputation of the ankle.

dynamic elastic response (DER) prostheses have been developed in order to return energy to the system. A key concept of these prostheses is that elastic energy is stored when they compress under loading and this energy is returned later in the activity when the limb is unloaded. A key criteria for the effective use of this energy is that it is able to return the energy at the right time, frequency and location. This is difficult in a generic high activity prosthesis as the energy requirements vary depending on the activity being undertaken. Specific to the countermovement (CMJ), if the energy stored in the prosthesis in the eccentric phase can be returned in the concentric phase then the DER prostheses should be able to contribute to the total work required at the joints. However, if the energy is not stored, or is not returned effectively, then the remaining joints will have to compensate for the prosthesis. It is unclear if a DER prosthesis will be able to make a useful contribution and if the amputees will be able to compensate sufficiently at the other joints to be able to achieve a jump.

There is some debate about the relative contribution of the joints to the total positive work produced in the concentric phase leading up to flight. Hubley & Wells (1983) suggested that the knee was the main producer of work, followed by the hip and then the ankle. In contrast Fukashiro and Komi (1987) found that the hip was the most important contributor, followed by the knee and the ankle. Vanezis & Lees (2005) suggested that these discrepancies could be the result of the high variability in the data and identified two key strategies of jumping, with emphasis on the knee or the hip.

The primary aim of this study was to examine the work done in the prosthetic ankle in storage and return and to assess the effect of the passive foot in jumping. The secondary aim was to determine the work compensations at the other lower limb joints.

METHODS: Participants: Six unilateral transtibial amputees (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 able bodied (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 and familiarise themselves with the jumping criteria and laboratory conditions. Ten maximal bilateral countermovement jumps were performed with arms akimbo 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 plates during landing. On average 13 trials 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 25 mm 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 of each dynamic CMJ trial.

Data Analysis: Jump kinetics and kinematics were calculated using Vicon Workstation software. Kinematic data were smoothed using a Woltering quintic spline (MSE = 15 mm) filter. The trial with the highest flight height was chosen for further analysis. Inverse dynamics using standard procedures were used to determine the net joint reaction components and the net joint moments at the ankle, knee and hip from the ground reaction force data associated with each foot. Joint power (the product of the net joint moment and joint angular velocity) and the work done in each phase (the time integral of the power production in the eccentric and concentric phases, as determined by the movement of the centre of mass (CoM) were calculated using standard procedures (de Koning and van IngenSchenau, 1994). All variables were normalised to body mass. To facilitate comparison with results in the literature, the magnitude of the results at each joint were summated to give an overall joint value. Flight height was defined by the CoM displacement (maximum height less height at take-off) as determined by the kinematic analysis. All other variables are presented for the AMPs as intact and affected limb separately. For the AB, the results are for the preferred and non-preferred jumping limb (and are presented under intact and affected for ease of analysis).

RESULTS:

Table 1 Flight height of the centre of mass and negative work done at the prosthetic ankle

Participant	FH (m)	Negative work at the prosthetic ankle ($W.kg^{-1}$)
AMP_1	0.24	-0.004
AMP_2	0.19	-0.002
AMP_3	0.17	-0.003
AMP_4	0.13	-0.005
AMP_5	0.10	-0.004
AMP_6	0.09	-0.005
$\overline{x}_{(AMP)}$ (± sd)	0.15±0.06	-0.004±0.001
$\overline{x}_{(AB)}$ (± sd)	0.31± 0.04	-0.1369±0.03

AMP flight height was lower compared to AB participants. There was little negative work done at the prosthetic ankle, indicating that little energy was absorbed in the eccentric phase (Table 1).

Positive work in the concentric phase at the intact ankle generally followed the trend of high to low, and was generally greater than for the AB participants. Very little work was done at the prosthetic ankle. The work done at both knees was similar and was lower than for the AB participants. There was no obvious trend at the intact or residual hip, however, the AMP participant with the highest jump achieved the greatest work at the hip and was symmetrical (Figure 1).

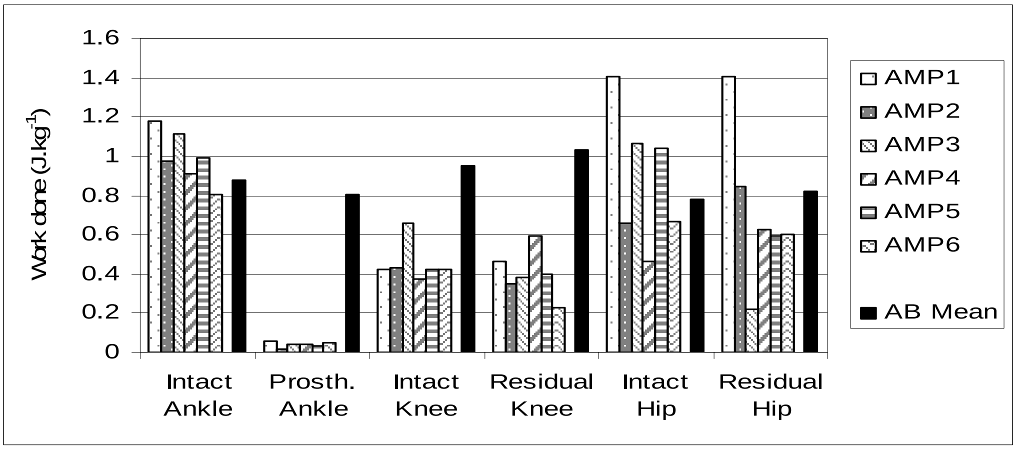

Figure 1: Positive work done at each joint in the concentric phase of jumping

The intact side dominated for overall positive work (Table 2). Every AMP produced more work at the intact compared with the prosthetic ankle (Table 2). When the intact and affected sides are added together to get an overall hip, knee and ankle work contribution, 5 out of 6 AMPs produced most work at the hips, followed by the ankles and then the knees. Amp 4 produced most at the hip, followed by the knee and then the ankle.

Table 2 Relative contribution of each joint to the total positive joint work in the concentric phase.

Participant	Intact contribution (%)				Prosthetic contribution (%)			
	Ankle	**Knee**	**Hip**	**Total**	**Ankle**	**Knee**	**Hip**	**Total**
AMP$_1$	24	9	28	**61**	1	9	28	**39**
AMP$_2$	30	13	20	**63**	1	11	26	**37**
AMP$_3$	32	19	31	**82**	1	11	6	**18**
AMP$_4$	30	12	15	**58**	1	20	21	**42**
AMP$_5$	29	12	30	**71**	1	12	17	**29**
AMP$_6$	29	15	24	**68**	2	8	22	**32**
$\bar{x}_{(AMP)}$ (± sd)	29± 3	13± 3	25± 6	**67± 8**	1± 0.4	12± 4	20± 8	**33± 9**
$\bar{x}_{(AB)}$ (± sd)	17± 3	18± 5	15± 6	**50± 7**	16± 3	20± 7	15± 7	**50± 7**

DISCUSSION: Vertical jumping is a fundamental skill common to numerous recreational activities and training strategies. It consist of clear phases, each with its own underlying performance criterion for successful execution. This makes it a valuable experimental model in assessing the cause and effect of human movement strategies for different population groups (Challis, 1998; Strike & Diss, 2005). As jumping is a multi-joint action that requires substantial muscular effort from the ankle, knee and hip joints, it was expected that biomechanical compensations would result from the amputation and that these would not be sufficient for amputees to jump effectively. The AMPs did not achieve flight heights equivalent to the AB participants who were matched for jumping experience. Only the AMP who jumped the highest reached a height which was similar to the lowest AB participant. It is clear that the prosthetic ankle did not sufficiently compensate for the intact ankle. Our first aim was to determine if the prosthesis was effective in performing negative work (energy absorption) in the eccentric phase and if this was returned effectively as positive work in the concentric phase. Although dynamic ankles are designed to store energy under loading and return this energy when the load is removed, the prosthetic ankle did not do this effectively in this movement. Only small amounts of negative work were recorded in the ankle in the eccentric phase. As a result there was little energy to be returned in the concentric phase, as indicated in the small positive work done at this joint. The dynamic nature of the prosthesis is not utilised effectively by AMPs in jumping. The second aim of the research was to determine how the other joints compensated for the ankle pathology. The other joints could not compensate effectively, with less work also recorded at the residual knee and hip compared to the AB participants. For the intact side the ankle and hip were the main joints at which compensations occurred, with the hip as the main source of work for all AMPs. When the intact and affected side work are added together, all AMPs except one produced most of the work at the hip, followed by the ankle and then the knee. Clearly the AMPs adopt the hip strategy as described by Venezis and Lees (2005). The lack of the biarticular gastrocnemius muscle clearly influences the knee mechanics on the affected side, but it also seems to influence them on the intact side. This is a result which requires further study.

CONCLUSION: In the absence of an intact ankle, AMPs did not reach the heights attained by experience matched AB participants. The work done by the prosthesis was not sufficient to replace the anatomical structure. There is a clear need for an accessible lower leg prosthesis for non-competitive amputees which will accommodate both everyday ambulation and more vigorous activities associated with a physically active lifestyle (Hafner et al, 2002). Continuous research into lower limb prostheses should aim to enhance amputee movement adapting the elastic energy storage and return properties of the prosthesis so that the magnitude, frequency and timing of the energy absorption and return is better suited to reduce the compensations required at the remaining joints and to enhance biomechanical performance.

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