

Lower limb intersegmental forces for below-knee amputee children during standing

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Abstract

The purpose of this investigation was to compare intersegmental knee and hip forces for below-knee amputee (BKA) and able-bodied children during standing. Three unilateral BKA children and 10 able-bodied children (7-9 years) were tested on four separate occasions at six month intervals. Three trials of external force and spatial data during standing were collected from each subject for each session. These data were utilised to determine the intersegmental forces at the knees and hips of the children using a static force analysis. Results indicated that in some instances the intersegmental forces for the BKA children were significantly greater than those of the able-bodied children and in other instances significantly lower ($p < 0.05$). In all cases, however, the values were substantially less than corresponding values for walking and running. The effects of the forces upon spatial orientations indicated significant differences between the two groups of children. The frontal plane prosthetic knee angle, the sagittal plane prosthetic and non-prosthetic knee angles, and the sagittal plane trunk angle were all greater for the BKA children when compared to able-bodied children. These differences may be the result of the anatomical structure of the amputee and/or the construction of the prosthesis.

Introduction

It has been previously reported that the ground-shoe weight distribution for prosthetic

and non-prosthetic limbs of below-knee amputee (BKA) children was not significantly different from that of able-bodied children (Engsberg *et al.*, 1989). However, the anterior-posterior weight distribution between the shoe and the ground for prosthetic and non-prosthetic feet was significantly different from able-bodied children (Engsberg *et al.*, 1989). More weight was applied to the forefoot of the prosthetic limb and more weight was applied to the rearfoot of the non-prosthetic foot than in the case of able-bodied children. It was concluded from this investigation that the benefit, detriment or irrelevance of these atypical loading patterns to the well-being of BKA children was unknown and that work should be conducted towards resolution of this issue.

The term detrimental load could refer to its magnitude, its direction or its distribution and could be detrimental from both short and long term perspectives. Short term perspective could be that the loads were related to pain, discomfort, premature fatigue. Long term perspective may indicate that the loads were related to degenerative joint disease. A direction towards understanding these loads and their potential effects could be to quantify them internally and compare them with similar values for able-bodied children. This quantification could be partially accomplished by considering the intersegmental forces at the joints of the lower limbs for these two groups of children. If the forces for the BKA children were significantly larger than those of able-bodied children and/or produced atypical spatial orientations then the possibility exists that they may be detrimental. If however, the

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loads were similar in direction and distribution to able-bodied children or were much smaller in magnitude than those occurring during other activities (e.g., walking or running) then they may not be detrimental. The purpose of this investigation was to compare intersegmental knee and hip forces for BKA and able-bodied children during standing.

Methods

Three unilateral BKA children and ten able-bodied children volunteered as subjects for this investigation. The children ranged in age from seven to nine years with the mean age being eight years. Each BKA child wore a SACH (solid ankle, cushioned heel) terminal device as a part of his/her prosthesis. The children visited the Human Performance Laboratory at The University of Calgary on four separate occasions at six month intervals. Three sets of data during standing were collected from each subject for each session. Ground reaction pressure data were collected from an EMED pressure system as previously described (Engsberg *et al.*, 1989). Spatial data were obtained from two Locam cameras (frontal and lateral views) operating at a rate of 20 Hz.

Joint centres and segmental endpoints were digitised from the film utilising a seven segment model (i.e., feet, legs, thighs, head-arms-trunk segment) and converted to three-dimensional data utilising the direct linear transformation (DLT) method (Abdel-Azis and Karara, 1975; Engsberg and Andrews, 1987). Figure 1 illustrates the right handed co-ordinate system (R) fixed (i) in the laboratory, (ii) to the distal aspect of the left leg, (iii) to the distal aspect of the left thigh and (iv) to the trunk segment. The latter three co-ordinate systems were used to describe the angular orientation of the three segments as a projection on to a plane. A left handed co-ordinate system (P) was used to describe the orientation of the right leg and thigh (Fig. 1). This left handed co-ordinate system was created in order that the positive Y axes always pointed laterally for the lower limbs and thus eliminate sign ambiguity in the data analysis in the frontal plane. For example, in the frontal plane (Fig. 1a) the angular orientation of the thigh was measured about the positive X_R or X_P axes from the positive Y_R or Y_P axes in the direction of the positive Z_R or Z_P axes, respectively.

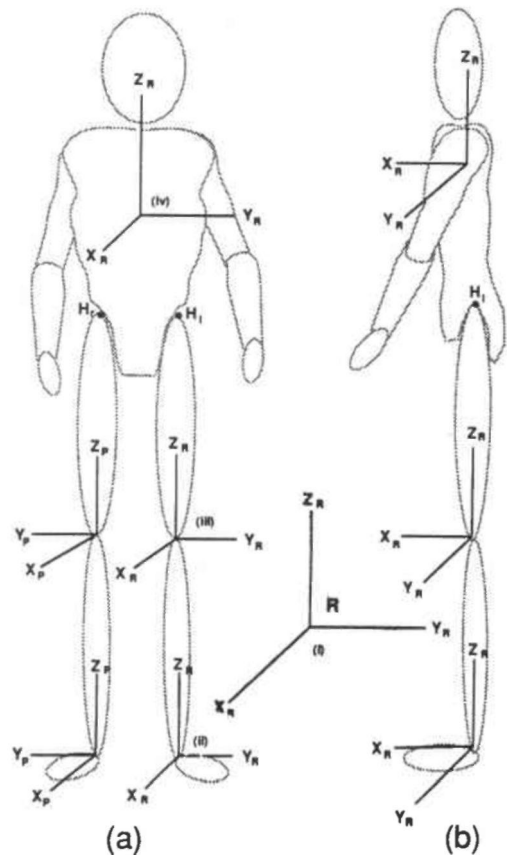


Fig. 1. The right and left handed laboratory co-ordinate system (i.e. R and P) fixed in the laboratory and at the distal aspects of the leg, thigh and trunk. This figure characterises the position of an able-bodied child from a frontal (a) and a lateral (b) perspective.

Pressure plate information was reduced to yield a resultant normal force and a point of application. It should be noted that in this analysis only normal forces were determined while shear forces were neglected. A dominant (D) and non-dominant (ND) foot was then declared for the limbs of the able-bodied children (Engsberg *et al.*, 1989). The dominant limb was defined to be the limb with larger average ground-foot force values. The non-dominant limb was the other limb.

Knowing the location of three points on the pressure plate allowed for transformation of the force data at its point of application to the same laboratory co-ordinate systems as the spatial data. The data were then transformed to local co-ordinate systems to provide for functionally relevant application of the data (Fig. 2). For

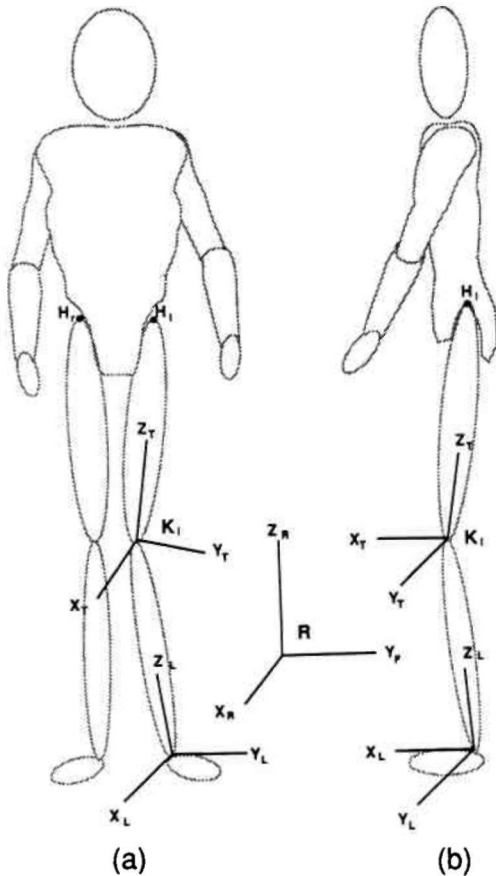


Fig. 2. The right and left handed local co-ordinate systems fixed on the segments at their distal ends. This figure characterises the position of a BKA child from a frontal (a) and a lateral (b) prosthetic leg perspective.

example, the local co-ordinate system produced an intersegmental force that was directed along the long axis of the segment. This force was identical to the intersegmental force obtained from the laboratory co-ordinate system (R) if the long axis of the segment was vertical. However, if the segment was not vertical the local co-ordinate system would continue to produce an intersegmental force that would be directed along the long axis of the segment, while the laboratory co-ordinate system (R) would produce a force that would still be vertical. This vertical force does not seem as functionally relevant in a non-vertical segment as would a force that was directed along the segment's longitudinal axis. The local co-ordinate system (T) for the left thigh was determined in the following manner:

$$Z_T = r_{H_i/K_i} \quad (1)$$

$$X_T = Z_T \times r_{H_r/K_i} \quad (2)$$

$$Y_T = Z_T \times X_T \quad (3)$$

where X_T , Y_T , Z_T represents the thigh co-ordinate axes and r_{H_i/K_i} , r_{H_r/K_i} represent position vectors from the left knee (K_i) to the left hip (H_i) and from the left knee to the right hip (H_r). The local right handed co-ordinate system for the left leg and local left handed co-ordinate systems for the right leg and thigh were determined in a similar fashion. These co-ordinate systems were utilised to determine the intersegmental forces at the knees and hips of the children following the inverse dynamics approach as previously described (Andrews, 1974; Lewallen *et al.*, 1986; Miller, 1987; Verstraete and Soutas-Little, 1989). However, since the children were only standing the inertia force vector was equal to zero and the analysis was reduced to a static force analysis. In addition, the intersegmental forces were acting upon the proximal ends of the two segments and forces were normalised by dividing by body weight.

In order to present the spatial data of this investigation from a clinical perspective, an approximation of the Q angle (i.e., frontal plane acute angle of the patellar tendon and patellar ligament) was made for the able-bodied, non-prosthetic and prosthetic knees of the children. The Q angle was estimated by determining the frontal plane angle formed by the hip, knee and ankle joint centres. Zero degrees represented a straight limb. A positive value represented a valgus condition of the leg with respect to the thigh. A negative value represented a varus condition of the leg with respect to the thigh. In addition, knee flexion angles were also determined from the same joint centres, but in this case the orientation was the sagittal plane. Zero degrees represented full knee extension while a positive value represented a knee in flexion. It should be noted that the segmental analysis incorporated five degrees of freedom since only two points were used to represent each segment. Thus any abnormal angular orientation of one segment with respect to another about a longitudinal axis (i.e., Z_T or Z_L axis) was not recorded. However, it was speculated that any substantial amounts of external or internal rotation of the thigh or leg would be observed by atypical foot orientation.

One-way analysis of Variance (ANOVA) was used to determine significant differences between variables. A Tukey Post Hoc analysis then defined which of the variables were significantly different at the 0.05 confidence level. The intersegmental forces in the X, Y, and Z directions in the local co-ordinate systems for the dominant and non-prosthetic, non-dominant and prosthetic, and prosthetic and non-prosthetic limbs were evaluated. In addition, the projected angular orientations (i.e., frontal and sagittal planes) of the legs and thighs for the able-bodied, non-prosthetic and prosthetic limbs of the children and the angular orientations of the trunks for the two groups of children were compared. No significant differences existed between the angular orientations of the trunk, right and left legs and thighs of the able-bodied children and these were combined to form a single set of data.

Results

Figures 3-5 present the average normalised intersegmental forces and standard errors acting at the proximal end of the leg and thigh for each leg type of the BKA and able-bodied children. Figure 3 displays the results for both segments in the Z direction (i.e., longitudinal), Figure 4 in the Y (i.e., anterior-posterior) direction and Figure 5 in the X (i.e., medial-lateral) direction. Significant differences between non-prosthetic and prosthetic (*), between non-prosthetic and dominant (x) and

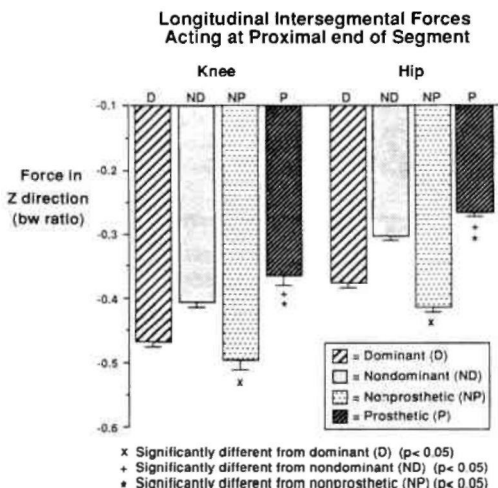


Fig. 3. Intersegmental forces normalised to a ratio of body weight (BW) acting in the Z direction (i.e. longitudinal) on the proximal end of the segment.

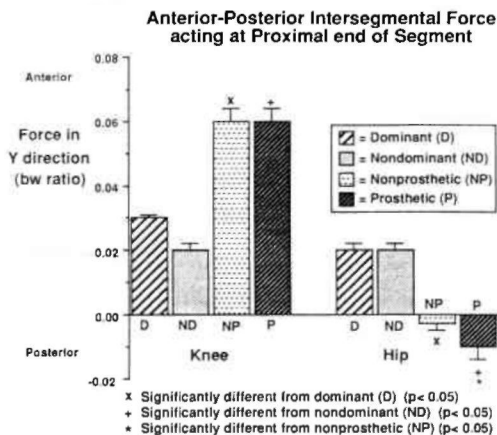


Fig. 4. Intersegmental forces normalised to a ratio of body weight (BW) acting in the Y direction (i.e. anterior-posterior) on the proximal end of the segment.

between prosthetic and non-dominant (+) are indicated. It was believed that these comparisons were most relevant since it was assumed that the non-prosthetic limb would be the dominant limb for the BKA children. This assumption seemed reasonable since two of the children were amputees due to a congenital abnormality and amputation occurred before one year of age. For the third BKA child, which foot was dominant prior to the amputation due to trauma was unknown. It was assumed that the non-prosthetic limb had become dominant if it had not been before the amputation. It should be noted that the changes from intersegmental knee forces acting on the leg to

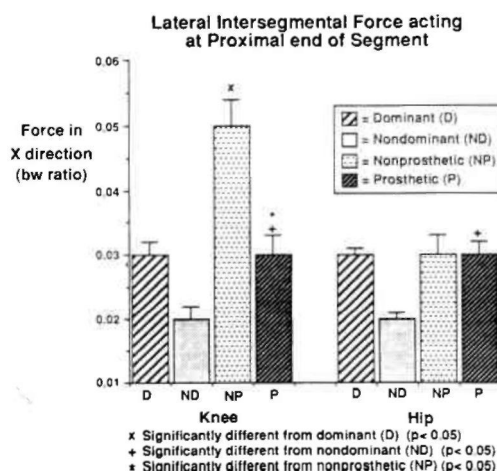


Fig. 5. Intersegmental forces normalised to a ratio of body weight (BW) acting in the X direction (i.e. medial-lateral) on the proximal end of the segment.

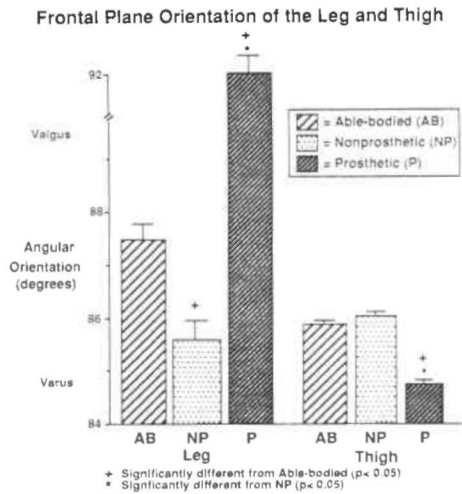


Fig. 6. Angular orientations of the leg and thigh in the frontal plane.

intersegmental hip forces acting on the thigh are not merely due to the subtraction of the weight of the distal segments. Since the results are presented with respect to the local coordinate systems they also reflect the change in segmental orientation. In addition, the intersegmental forces do not necessarily reflect the articular surface contact forces or forces due to muscular contractions.

The spatial effects of the intersegmental forces are presented in Figures 6-9. Frontal and sagittal plane leg and thigh angular orientations are indicated in Figures 6 and 7, respectively.

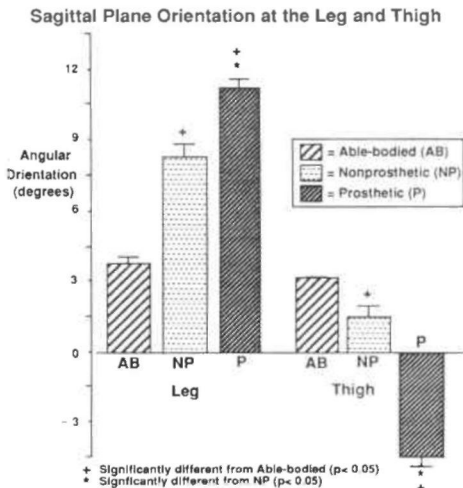


Fig. 7. Angular orientations of the leg and thigh in the sagittal plane.

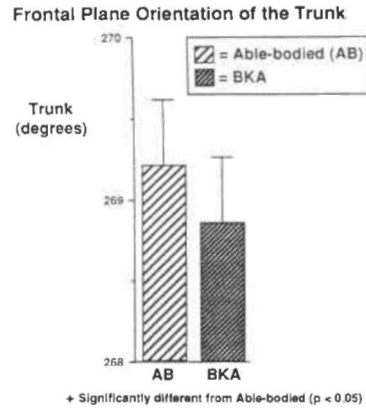


Fig. 8. Angular orientations of the trunk in the frontal plane.

Significant differences from able-bodied (+) and from non-prosthetic (*) are indicated.

Q angles and sagittal plane knee flexion angles for the able-bodied, non-prosthetic and prosthetic knees of the children are presented in Table 1. The slight valgus condition of the prosthetic leg relative to the knee (i.e., the prosthetic leg was oriented lateral to the knee) is pictorially displayed in Figure 2a. For comparison, the same orientation for the able-bodied children is displayed in Figure 1a. The sagittal plane orientation of the prosthetic leg and thigh of the BKA children is pictorially displayed in Figure 2b and that for able-bodied children is presented in Figure 1b.

Discussion

The intersegmental forces for the non-prosthetic and prosthetic knees and hips were significantly different from the dominant and non-dominant joints of the able-bodied children, respectively. In some instances they were slightly greater than able-bodied and in others slightly less than able-bodied. If the magnitudes of the intersegmental loads are considered, the values reported here do not appear to be substantially large when compared with other activities. The present investigation

Table 1. Q-angles and sagittal plane knee flexion angles for able-bodied, non-prosthetic and prosthetic limbs of subjects.

Leg type	Q-angle (degrees)	Knee flexion angle (degrees)
Able-bodied	1.0	0.2
Non-prosthetic	-0.3	7.2
Prosthetic	7.3	14.2

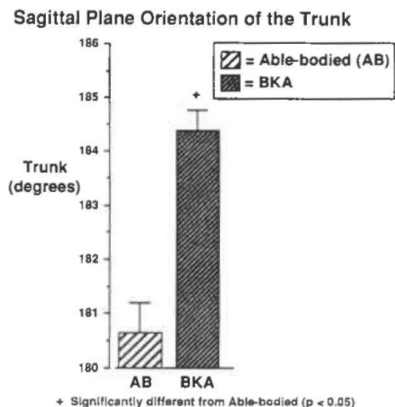


Fig. 9. Angular orientations of the trunk in the sagittal plane.

derived intersegmental forces of up to about 0.5 body weight for standing. However, it has been reported that intersegmental joint forces for walking of BKA children may be up to about 1.5 body weight (Lewallen *et al.*, 1986; Engsborg *et al.*, In Press). In addition, intersegmental forces for running may be about 2.0 body weight (Miller, 1987) for BKA adults. Thus it would not appear that the intersegmental forces during standing would be detrimental to the well-being of BKA children. Nevertheless it should be noted that the two additional factors, articular surface contact forces and their distribution, were not considered in this analysis and could prove to be detrimental to these children. Further investigation in this area is warranted.

The spatial results from the forces displayed differences between the two groups of children. Primarily, (1) the frontal plane prosthetic knee angle (i.e. Q angle), (2) the sagittal plane prosthetic and non-prosthetic knee angles and (3) the sagittal plane BKA trunk angle were different from those of the able-bodied children. A number of possible conditions may exist to explain these orientation differences. Two of the three BKA children in the present investigation were congenital amputees with fibular hemimelia. This condition often results in a valgus orientation of the leg with respect to the thigh (Fig. 2a) and thus a larger than able-bodied Q angle. It could be therefore speculated that these observed differences may not exist if additional subjects without this valgus condition were measured.

The greater than able-bodied sagittal plane prosthetic knee flexion angle (i.e., 14.2

degrees) could be the result of the socket design. For example each of the three subjects were fitted with PTB (patellar-tendon-bearing) sockets. It has been reported that if a PTB socket is so constructed that slight knee flexion is imposed, then the patellar ligament is better able to accept larger vertical loads during activities than if flexion was not imposed (New York University Medical Center, 1987). In addition, prosthetists often impose knee flexion when they construct the sockets to reduce the valgus condition of the leg with respect to the knee of some amputee patients. This was the case for two of the BKA children. Finally, while it was not the case for any of the three subjects in this investigation, a knee flexion contracture would create a sagittal plane flexion condition. Explanations for the sagittal plane non-prosthetic knee flexion did not abound, however this condition could be related to stability, leg length discrepancy, improperly aligned prosthesis or an uncomfortable socket. No measure of these factors was performed. The sagittal plane forward trunk angle of the amputees (Fig. 9) could be related to the prosthetic knee flexion.

It is apparent from these spatial results that the BKA children assume a distinctly different posture from that assumed by able-bodied children. The forces producing this postural orientation are different from able-bodied and may be the result of the imposed structure of the prosthesis and the lower limb. It would appear that monitoring the posture of the group of BKA children for an extended period of time to determine if this trend would continue may be valuable. In addition, measuring the posture of BKA adults to consider if the postural orientation of this population is the same as BKA children may also prove helpful.

Summary

This investigation measured the intersegmental knee and hip forces for BKA and able-bodied children. The significant differences observed for the internal force systems between groups of children may not be harmful to the BKAs since their magnitudes were substantially lower than those for walking and running. However, contact forces between articulating bones and their distribution were not determined. The effect of the loads on the posture of the BKA children produced

significant differences from able-bodied children. Without additional information from BKA adults and longitudinal information from BKA subjects, the influence of this atypical posture cannot be determined at this time.

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