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Normative ground reaction force data for able-bodied and trans-tibial amputee children during running

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Abstract

The purpose of this investigation was to develop normative ground reaction force data for able-bodied (AB) and trans-tibial amputee (TTA) children during running. Two hundred AB (mean age 9.4 years, range 7–12) and 21 TTA (mean age 11.1 years, range 5–17) children ran (2.2 m/s±10%) over a force platform. Ground reaction force data were normalized, averaged within groups and plotted to produce force-time curves characterizing the different leg types (i.e. able-bodied, non-prosthetic and prosthetic). In addition, discrete variables characterizing the leg type differences were determined. One way ANOVA determined significant differences between variables and a TukeyB Post Hoc analysis defined which variables were significantly different ($p<0.05$). Results generally indicated differences between the three leg types with the non-prosthetic leg indicating greater forces than the prosthetic and AB legs. The results of this investigation provide normative ground reaction force data for both AB and TTA children during running and can be used for comparison with other groups of children.

Introduction

In order to assess the benefit, detriment, or irrelevance of a particular change in a prosthesis (e.g. new socket design or new terminal device) it is often desirable to compare measured variables with established norms. If normative data do not exist then the effects of the particular change are more difficult to judge. In the case of a trans-tibial amputee (TTA) child, two sets of normative data appear desirable: data from able-bodied (AB) children and data from other TTA children. In both cases comparisons can be made to determine how closely the TTA child matches the respective groups. While normative data for both AB and TTA children exist for walking (Engsberg *et al.*, 1993; Sutherland *et al.*, 1988), none exist for running. The purpose of this investigation was to develop normative ground reaction force data for AB and TTA children during running.

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Methods

Two hundred AB (mean age 9.4 years, range 7–12) and 21 TTA (mean age 11.1 years, range 5–17) children volunteered to participate in this investigation. The characteristics describing the AB and TTA children are presented in Tables 1 and 2, respectively. All children were given a

Table 1. AB subject characteristics.

Age Group Years	Males (no.)	Females (no.)	Height (cm)	Mass (kg)
7–8	36	58	130	28
st.dev.			(7)	(6)
9–10	28	31	140	34
st.dev.			(7)	(7)
11–12	26	21	148	39
st.dev.			(6)	(6)
total	90	110		
mean			136	32
st.dev.			(10)	(8)

Table 2. TTA subject characteristics

Subject number	Age (years)	Gender	Height (cm)	Mass (kg)	Amputation	Foot type	Socket type	Suspension
04	8	m	124	20	left	SACH	PTS	Condylar
05	10	f	117	19	left	SACH	PTB	Condylar
06	11	m	147	43	left	Flex	PTB	Sleeve
14	17	m	168	63	right	Flex	PTB	Sleeve
32	14	m	155	49	right	SACH	PTB	Condylar
33	8	m	130	28	right	SACH	PTB	Condylar
34	12	m	144	37	right	Seattle	PTB	Fig of 8
36	12	m	155	54	left	Flex	PTB	Sleeve
37	5	m	116	22	left	SACH	PTB	Condylar
38	5	m	113	20	left	SACH	PTB	Sleeve
39	13	m	140	37	right	Single axis	PTB	Sleeve
43	11	m	138	29	right	Seattle	PTB	Condylar
46	12	m	178	65	right	Seattle	PTB	Th.corset
51	17	m	170	66	left	SACH	PTB	Condylar
52	11	m	130	29	right	SACH	PTB	Condylar
53	6	m	112	20	right	Flex	PTS	Condylar
54	12	f	144	32	right	SACH	PTB	Condylar
55	15	f	160	42	left	Seattle	PTB	Condylar
56	13	f	153	49	left	Seattle	PTB	Condylar
59	15	m	171	60	left	SACH	PTB	Condylar
60	7	m	113	19	right	SACH	PTB	Condylar
mean	11		142	38				
st.dev.	(3.6)		(21)	(16)				

physical examination by a pediatric orthopaedic surgeon and children not deemed able-bodied were excluded from the investigation. AB children were tested over a two week period during which approximately 20 children visited the Human Performance Laboratory each day. TTA children were tested over a one week period during which from 2–5 children visited the laboratory each day.

Ground reaction force data (1,000Hz) were collected during running support. For the AB children one trial was collected from each foot whereas for the TTA children at least three trials were collected from each foot. The same nominal rate of running (2.2 m/sec±10%) was enforced for all trials and was monitored by photocells spaced 2.4 m apart.

To allow for intersubject comparisons ground reaction force data were normalized by dividing by subject weight and contact time on the plate was normalized to a value of 1 (time 0 was touch down of the foot and time 1 was take off) (Engsberg *et al.*, 1991). These data were then averaged within groups and plotted to produce force-time curves characterizing the different leg types (i.e. able-bodied, non-prosthetic and prosthetic). Since the time of occurrence of relative maxima and minima forces for the leg types were not constant, the averaging process did not highlight the differences between leg types. Hence discrete variables characterizing these differences were determined (Andriacchi *et al.*, 1977; Engsberg *et al.*, 1991). For the vertical force-time curves, a slope, two local maxima, a local minimum, local impulses, total impulse, and local times of support were determined. For the anteroposterior force-time curves, two local maxima, impulses for the retarding (i.e. force applied by the foot in the anterior direction) and propulsive (i.e. force applied by the foot in the posterior direction) phases, associated time components, and total impulse were recorded. Impulses for the medial and lateral force components, respective maxima, and durations were compiled from the medio-lateral force-time traces.

One way ANOVA determined any significant differences between variables and a TukeyB Post Hoc analysis defined which variables were significantly different ($p<0.05$). Differences between variables for:

1) the right and left legs of the AB children;
2) ages of the AB children;
3) gender of the AB children;

4) legs of the AB children and the non-prosthetic legs of the TTA children;
5) legs of the AB children and prosthetic legs of the TTA children;
6) non-prosthetic and prosthetic legs of the TTA children; and
7) foot type and suspension of the TTA children were compared.

Results

Figures 1, 2 and 3 present the average force-time curves (i.e. vertical, anteroposterior and mediolateral) for the different leg types during running (i.e. able-bodied, prosthetic, non-prosthetic). Means and standard deviations of the vertical, anteroposterior and mediolateral discrete variables for the AB and TTA children appear in Tables 3, 4, and 5, respectively. For the AB children there were no significant differences for the discrete variables between:
1) right and left legs;
2) males and females; and
3) age.

Thus the respective values for the AB children were averaged to form one set of data (n=400) (Rosner, 1982). In addition, no significant differences were found for foot types or suspensions and the data for the TTA children were also grouped to form a single set of values. Significant differences existed between the non-prosthetic and prosthetic values of the TTA children, and between the TTA children and the able-bodied children. Tables 3, 4 and 5 indicate numerically the similarities and differences between the leg types of the two groups of children that could not be accomplished through Figures 1, 2 and 3.

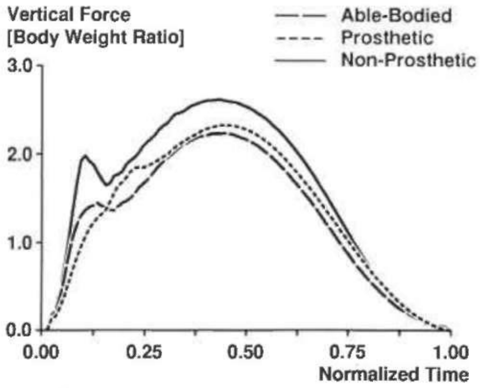

Figure 1. Average vertical force-time curves for the legs of able-bodied children and the prosthetic and non-prosthetic legs of TTA children.

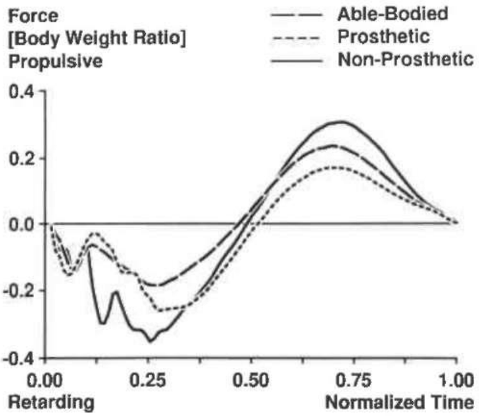

Figure 2. Average anteroposterior force-time curves for the legs of able-bodied children and the prosthetic and non-prosthetic legs of TTA children.

The figures clearly indicate differences between the leg types of the children. For example, in the vertical-force time curves (Fig. 1) the first peak that generally characterizes heel-toe running in adults is prominent in the non-prosthetic leg of the TTA children, becomes less prominent for the AB children and is not evident for the prosthetic leg. For the anteroposterior force-time curves (Fig. 2) there appears to be more abrupt changes in magnitude for the initial phase of the curve for the TTA children than the AB children. In addition, during the final phase, results for the AB children appear to fall between the non-prosthetic and prosthetic legs. For the medio-lateral force-time curves (Fig. 3) the non-prosthetic legs of the TTA children appear to have the same general shape as that of the AB children, however the magnitudes are

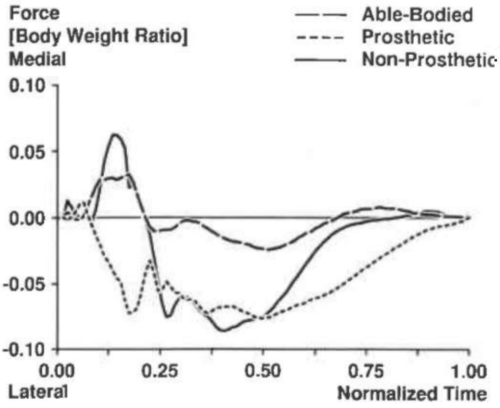

Figure 3. Average mediolateral force-time curves for the legs of able-bodied children and the prosthetic and non-prosthetic legs of TTA children.

substantially greater. During the first 25% of the mediolateral curve the prosthetic legs of the amputee children are different from the other leg types since they produce a predominantly lateral force. During the remainder of support the curve is similar to that of the non-prosthetic leg.

For the vertical force-time variables (Table 3) the maximum force (ZMax2) during the latter phase of support was not significantly different between leg types, but the total impulse for the non-prosthetic leg was significantly different from the legs of the AB children. In the antero-posterior direction (Table 4) the absolute maximum in the posterior direction (PMax) and the impulse in that direction (PImp) indicate significant differences between groups. The non-prosthetic limb was significantly greater than the prosthetic limb and the limbs of the AB children for both variables. The prosthetic limb was significantly less than the limbs of the AB children for both variables. For the medio-lateral variables (Table 5) it can be observed that the results for the prosthetic legs indicated

Table 3. Means and standard deviations for vertical force-time variable for able-bodied (AB), non-prosthetic (NP) and prosthetic (P) limbs during running.

Leg	ZImp1 BW×ratim	ZMax1 BW	ZT1 ratim	Slope BW×ratim	ZImp2 BW×ratim	ZMax2 BW	ZT2 ratim	ZMin BW	ZImpTo BW×ratim
AB (N=400)	0.19 (0.08)	1.90 (0.58)	0.18 (0.05)	17.1 (7.6)	1.18 (0.18)	2.44 (0.33)	0.82 (0.05)	1.34 (0.37)	1.37 (0.20)
NP (N=22)	0.25+ (0.11)	2:11 (0.48)	0.20 (0.07)	20.9+ (10.0)	1.22 (0.20)	2.54 (0.27)	0.80 (0.07)	1.57+ (0.39)	1.47+ (0.15)
P (N=22)	0.28+ (0.17)	1.89 (0.65)	0.22+ (0.08)	15.1* (12.3)	1.15+ (0.21)	2.56 (0.46)	0.78+ (0.08)	1.77+ (0.65)	1.42 (0.22)

BW=body weight
ratim=ratio of total single leg support time
ZImp1=area under vertical force-time curve from touch down to local minimum
ZMax1=first local maximum on vertical force-time curve
ZT1=time from touch down to ZMin
Slope=slope of line from touch down to ZMax1
ZImp2=area under vertical force-time curve from local minimum to take off
ZMax2=second local maximum on vertical force-time curve
ZT2=time from ZMin to take off
ZMin=local minimum on vertical force-time curve
ZImpTo= total area under vertical force-time curve
+Significantly different from able-bodied ($p<0.05$)
*Significantly different from non-prosthetic ($p<0.05$)

Table 4. Normalized means and standard deviations for the measured anteroposterior (retarding-propulsive) force-time variables during running

Leg	RImp BW×ratim	RMax BW	RTime ratim	PImp BW×ratim	PMax BW	PTime ratim
AB (N=400)	0.081 (0.032)	0.42 (0.19)	0.46 (0.06)	0.078 (0.021)	0.27 (0.06)	0.54 (0.06)
NP (N=22)	0.091 (0.032)	0.45 (0.17)	0.46 (0.09)	0.093+ (0.040)	0.36+ (0.16)	0.54 (0.09)
P (N=22)	0.086 (0.038)	0.39 (0.14)	0.46 (0.11)	0.063+* (0.040)	0.23+* (0.15)	0.54 (0.11)

BW=body weight
ratim=ratio of total single leg support time
RImp=area under retarding portion of antero-posterior force-time curve
RMax=maximum value for retarding force in the anteroposterior force-time curve
RTime=time from touch down to change from retarding to propulsive force
PImp=area under propulsive portion of anteroposterior force-time curve
PMax=maximum value for propulsive force in anteroposterior force-time curve
PTime=time from change from retarding to propulsive force to take off
+Significantly different from able-bodied ($p<0.05$)
*Significantly different from non-prosthetic ($p<0.05$)

Table 5. Normalized means and standard deviations for the measured mediolateral force-time variables during running

Leg	MImp BW×ratim	MMax BW	MTime ratim	MImp BW×ratim	LMax BW	LTime ratim
AB (N=400)	0.022 (0.024)	0.14 (0.11)	0.47 (0.29)	0.034 (0.037)	0.14 (0.11)	0.53 (0.29)
NP (N=22)	0.018 (0.019)	0.16 (0.12)	0.39 (0.24)	0.048 (0.038)	0.18 (0.11)	0.61 (0.24)
P (N=22)	0.016 (0.023)	0.13 (0.10)	0.29+ (0.24)	0.042 (0.027)	0.20+ (0.18)	0.71+ (0.24)

BW=body weight
ratim=ratio of total single leg support time
MImp=area under medial force portion of medio-lateral force-time curve
MMax=maximum value for medial force in the mediolateral force-time curve
MTime=time from touch down to change from medial to lateral force
LImp=area under lateral force portion of medio-lateral force-time curve
LMax=maximum value for lateral force in mediolateral force-time curve
LTime=timefrom change from medial to lateral force
+Significantly different from able-bodied ($p<0.05$)
*Significantly different from non-prosthetic ($p<0.05$)

significant differences when compared to the AB legs. Greater values were obtained for the maximum force in the lateral direction (LMax) and for the time spent applying force in the lateral direction (LTime).

Discussion

The purpose of this investigation was to determine normative ground reaction force data for AB and TTA children during running. Four limitations appear noteworthy. The first is that the externally measured ground reaction force data may not reflect the internal loading of the joints of the lower limbs. Other forces such as those of muscles and ligaments also contribute to this load. The second limitation was with respect to the running speed. A number of methods exist for comparing the running speeds of the subjects (e.g. fixed speed, fixed cadence, freely chosen speed) with each method having its own advantages and limitations. Since it has been shown that rate of walking can influence force variables for children with trans-femoral amputation, (Zernicke *et al.*, 1985) the same rate of running was used for all subjects in the present investigation. This chosen speed was based upon preliminary pilot investigations performed in the laboratory.

The third limitation was that this investigation determined normative data for TTA children, disregarding inter-subject prosthetic differences (i.e. foot types or suspension). While the design of this study was not well suited for considering the potential effects of these factors, the results were however, examined. In general, no significant differences were found between the variables for foot type and suspension.

The fourth limitation relates to the differences between the average force curves presented in Figures 1, 2 and 3 and the quantification of discrete variables derived from individual subject force curves presented in Tables 3, 4 and 5. The apparent discrepancy of results between the figures and the tables arises from the averaging process used to derive the force curves. Since the maximum values for a particular variable do not occur at the same instant in time for all subjects and leg types the averaged curves will not reflect the peak value displayed in the Table. On the other hand, the discrete variables determined from each individual curve and presented in the Tables will provide the true value since time of occurrence was not used in the determination of the value. For example, the ZMax1 variable in Table 3 reports values of 1.90, 2.11 and 1.89 for the AB, non-prosthetic and prosthetic legs, respectively. However, Figure 1 indicates a ZMax1 value for AB children to be about 1.5, ZMax1 value for non-prosthetic leg of the TTA to be about 2.0, and Zmax1 value for the prosthetic leg to be about 1.9 (i.e. if the levelling of the curve at about 0.25 of the cycle is used as the average ZMax1 value). Thus it is important to view the curves as providing average shapes characterizing general differences between leg types and the tables as providing accurate discrete information for particular variables associated with the curves.

Prince *et al.* (1992) presented local maxima in the vertical, anterior, and posterior directions for a group of young TTA adults (n=9, mean age of 16 years). They found significantly greater values for the ZMax2 variable for the non-prosthetic leg when compared to both the prosthetic legs and legs of the AB. The present investigation did not find those differences and indicated no differences between the three leg types. Even though Miller (1987) did not present discrete values for the prosthetic and non-prosthetic limbs of TTA adults (n=4, mean age of 40 years) her figures concur with the results of the present investigation suggesting that approximately the same values occurred for the non-prosthetic and prosthetic legs. In support of the results presented by Prince *et al.* (1992) and in contrast to the results of the present investigation and of Miller (1987) the authors of this paper have reported greater ZMax2 values for the children of this investigation during walking (Engsberg *et al.*, 1993). The results indicated that the non-prosthetic leg had a significantly greater ZMax2 value than the prosthetic leg and the legs of AB children. In addition, it was reported that the prosthetic leg force was significantly less than the AB leg force for the ZMax2 variable. Further investigation appears warranted in this regard.

In the anteroposterior directions Prince *et al.* (1992) reported significant differences for the RMax variable between the non-prosthetic legs and the AB legs and between the prosthetic legs and the non-prosthetic legs. The present investigation found no significant differences in RMax values between leg types. For the PMax variable Prince *et al.* (1992) reported significant differences between the prosthetic leg and both the non-prosthetic and AB legs. The present investigation supported these relationships and also found significant differences between the non-prosthetic and the AB legs. The differences in the results between the two investigations may be explained by subject age, subject numbers, and different prostheses.

Prince *et al.* (1992) reported that the ZMax2 and the ZImpTo variables were significantly greater (rigid keel only) in non-prosthetic legs when compared to similar values of AB controls. Similar results for the same variables and for approximately the same group of subjects as in the present investigation have been reported for walking (Engsberg *et al.*, 1991 and 1993). In contrast to these results the present investigation did not concur with these findings. A potential explanation could be related to the possible effects of foot types since Prince *et al.* (1992) reported no significant differences for the two variables for flexible keel feet. Further investigation is necessary in this regard.

Prince *et al.* (1992) reported that the PMax and PImp variables were significantly different between the prosthetic legs and the legs of the AB subjects. These loading differences, also occurring in the present investigation, have been reported for walking (Engsberg *et al.*, 1991 and 1993). The similarity of these results appears to indicate that despite the type of terminal device used, the prosthetic legs do not generate propulsive forces similar to those produced by intact legs. The objective of the authors' research in this area is to enable TTA children to walk and run in the same way as AB children. The accomplishment of this objective would however require the development of a prosthesis which allows the prosthetic leg to produce the same forces as those of intact legs.

Conclusions

The results of this investigation provide normative ground reaction force data for both AB and TTA children during running. The results for the AB children can be used for comparison with TTA children and with any other groups of children (e.g. children with cerebral palsy) if similar data are determined. The results for the TTA children can be used to determine if TTA children are functioning similarly to other TTA children. Since the results indicate basic differences between TTA and AB children during running, research should be directed towards eliminating these differences.

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