

The Effect of Foot and Ankle Prosthetic Components on Braking and Propulsive Impulses During Transtibial Amputee Gait

Robert J. Zmitrewicz, MS, Richard R. Neptune, PhD, Judith G. Walden, MPH, William E. Rogers, MS, Gordon W. Bosker, MED, CPO, LPO, CPed

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Objective: To assess the influence of energy storage and return (ESAR) prosthetic feet and multi-axis ankles on ground reaction forces and loading asymmetry between lower limbs in transtibial amputees.

Design: Subjects wore 2 different prosthetic feet with and without a multi-axis ankle and were analyzed using a blind repeated-measures multivariate analysis-of-variance design.

Setting: Gait analysis laboratory.

Participants: Fifteen healthy unilateral transtibial amputees (>55y) who had an amputation at least 1 year before testing because of vascular disorders.

Interventions: Not applicable.

Main Outcome Measures: The anteroposterior ground reaction force impulse, peak ground reaction forces, and braking and propulsive impulse duration were analyzed as subjects walked at a self-selected speed while wearing each of the 4 foot-ankle prosthesis combinations. Statistical analyses were used to determine if there was a significant foot, ankle, or foot-ankle interaction effect on the outcome measures for each foot ($P < .05$).

Results: Amputees generated a significantly greater propulsive impulse with the residual leg when wearing a multi-axis ankle with the ESAR and non-ESAR foot, which improved the propulsive symmetry between the residual and intact legs. There was no prosthetic foot effect on these measures. There were no significant differences in the peak residual-leg braking or propulsive ground reaction forces or the impulse durations due to the prosthetic foot, ankle, or foot-ankle interactions, although an increase in the propulsive impulse duration approached significance ($P = .062$) with a multi-axis ankle.

Conclusions: These results suggest that amputee gait may improve with the prescription of multi-axis ankles that allow

for greater propulsive impulses by the residual leg, which improve the loading symmetry between legs.

Key Words: Amputees; Rehabilitation; Walking.

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THE PRESCRIPTION OF the optimal prosthetic components to ensure a successful amputee rehabilitation remains a challenging problem, because there are no generally accepted clinical guidelines based on objective data.¹ Prescription of prosthetic feet is often derived from the successful clinical experience of a prosthetist rather than biomechanic data and scientific justification for specific prosthetic components.² The lack of biomechanic guidelines is especially pertinent with regard to energy storage and return (ESAR) feet. Mechanically, ESAR feet store elastic energy in early stance and midstance, and they release it in late stance and preswing to provide some of the mechanical energy normally provided by the ankle plantarflexors. However, previous studies often have not produced statistically significant improvements in various kinesiological measures (eg, preferred walking speed, cadence, stride length, muscle activity, energy expenditure) when amputees wore ESAR versus non-ESAR feet (eg, conventional solid-ankle cushion-heel [SACH] feet). (See Hafner et al² for review.)

A recent survey of lower-leg amputees showed that balance confidence and stability correlated strongly with walking performance and social activity.³ Stability is increased with a foot-flat posture, which is delayed in early stance relative to nonamputees because of limited prosthesis ankle range of motion (ROM)⁴ and the absence of plantarflexors to actively provide a foot-flat posture. As a result, the amount of time amputees spend with heel-only contact with the ground before achieving a foot-flat posture is nearly twice that of nonamputees,⁵ which may result in compromised balance and stability. In addition, a recent comparison of an ESAR foot with a conventional non-ESAR foot suggested that patient preference for the ESAR foot was based on increased power absorption in the prosthetic ankle during weight acceptance, as well as increased ankle ROM that allowed a foot-flat posture in response to uneven terrain.⁶ Thus, ankle ROM appears to be an important characteristic when designing and selecting foot-ankle components. To improve ankle ROM, prosthetic feet are often combined with a multi-axis ankle that allows full foot ROM with respect to the lower-leg prosthesis. However, it is not clear how the multi-axis ankle affects the biomechanic performance of the foot.

Ground reaction forces are important biomechanic measures to analyze because amputees are at increased risk of developing joint disorders in the intact leg as a result of increased leg loading,^{4,7,8} and the ground reaction forces reflect the motion of the body's center of mass. Studies have shown the intact leg

From the Department of Mechanical Engineering, University of Texas, Austin, TX (Zmitrewicz, Neptune); Physical Medicine and Rehabilitation Service, South Texas Veterans Health Care System/Audie L. Murphy Division, San Antonio, TX (Walden); and Department of Rehabilitation Medicine, University of Texas Health Science Center, San Antonio, TX (Rogers, Bosker).

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Reprint requests to Richard R. Neptune, PhD, Dept of Mechanical Engineering, University of Texas, 1 University Station C2200, Austin, TX 78712, e-mail: rneptune@mail.utexas.edu.

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often experiences increased anteroposterior (AP) and vertical ground reaction forces compared with the residual leg⁹⁻¹² and those observed in nonamputees.¹⁰ Despite the compliant characteristics of ESAR feet, the ground reaction force patterns of subjects wearing ESAR feet are very similar to those of subjects wearing non-ESAR feet, although some studies have found important differences. During weight acceptance on the intact leg, ESAR feet tend to decrease the vertical ground reaction force relative to non-ESAR feet.^{9,11,13} Others have suggested that ESAR feet decrease the intact-leg vertical ground reaction force because of increased prosthesis ankle ROM that allows the heel to stay in contact with the ground throughout stance; this results in a lower body center of mass during intact-leg swing, which allows for an improved weight transfer during the subsequent loading response.¹¹ Although previous studies generally do not report any changes in the propulsive (positive AP) force of the intact leg, studies^{2,11,13} analyzing ESAR feet have shown increased propulsive forces of the residual leg.

Despite these previous studies analyzing amputee ground reaction forces, there has been little analysis of braking and propulsive impulses during walking. The ground reaction force impulse (ie, time integral of the ground reaction force) is an important biomechanic measure to analyze because it encompasses both the magnitude and duration of ground reaction forces and therefore provides insight into how amputees are able to modulate braking and propulsion. Impulse has previously been used to assess gait asymmetry in transtibial amputee walking and running, and it was found to be an effective measure because amputees often compensate by modulating both force and time parameters.^{12,14} As a result, impulse analysis was able to show greater asymmetry between the residual and intact legs during running than the ground reaction forces alone.¹⁴ However, to our knowledge, no study has analyzed the influence of multi-axis ankles combined with ESAR feet on the braking and propulsive impulses during amputee walking, which would provide insight into how amputees provide the necessary body forward propulsion and the degree of loading asymmetry between the residual and intact legs.

The purpose of this study was to examine the influence of ESAR feet and multi-axis ankles on the ability of amputees to generate ground reaction forces and corresponding impulses during walking at their self-selected speeds. Specific quantities examined included the braking and propulsive impulses and the corresponding peak ground reaction force and impulse duration. We hypothesize that ESAR feet and multi-axis ankles improve the ability of the residual leg to generate braking and propulsive impulses and thus provide more symmetry loading between the intact and residual legs.

METHODS

Participants

Fifteen elderly, unilateral transtibial amputees were recruited for this study (14 men, 1 woman; age, 58.1 ± 6.7 y; height, 173.6 ± 7.3 cm; mass, 91.6 ± 23.0 kg) from the South Texas Veterans Affairs Medical Center (Amputee and Rehabilitation Medicine Clinics) and the University of Texas Health Science Center (Amputee and Rehabilitation Medicine Clinics). All subjects were at least 55 years of age and wore a well-fitting, endoskeletal prosthesis, and in each case the amputation was performed for vascular disorders at least 1 year before testing. All subjects were healthy and active, and they used their prostheses on a daily basis for normal gait activities. Recruitment and study procedures were approved by the institutional review boards of the University of Texas Health Science Cen-

ter at San Antonio and the South Texas Veterans Health Care System. All subjects provided written informed consent before data collection.

Prosthetic Foot Selection

Four combinations of foot-ankle components were fit in random order to each patient's existing prosthesis. The foot-ankle components were selected to isolate and characterize the effects of both increased ankle ROM and energy storage features. This was a blind study in that subjects did not know which prosthetic components they were wearing at any time during the study. To characterize the effects of ESAR versus non-ESAR feet, a Carbon Copy II (CCII) foot^a was compared with a SACH foot.^a The prosthetic feet were tested with and without a multi-axis (MA) ankle^a to assess the influence of ankle ROM on the ground reaction force variables. The 4 foot-ankle prosthesis combinations evaluated were as follows: (1) SACH foot, (2) SACH foot with multi-axis ankle (SACH-MA), (3) CCII foot, and (4) CCII foot with multi-axis ankle (CCII-MA). The foot-ankle components were aligned by a certified prosthetist using standard clinical procedures, and subjects were given a 4-week acclimatization period to establish a consistent gait pattern. Subjects were asked to use the prosthesis as the primary device, and a step counter^b was used to monitor their use.

Instrumentation

A 6-camera motion-capture system^c and 4 overground force-plates^d were used to collect the experimental walking data. The forceplates were placed in tandem order and covered with floor tiles to prevent foot targeting. Kinematic data were recorded to determine each patient's walking speed and temporal parameters. Reflective markers were attached to both lower legs using a modified Helen Hayes marker set with markers on the second metatarsal head, lateral malleolus, heel, lateral midleg, lateral condyle of the knee, lateral midthigh, anterior superior iliac spine, and sacrum. For the prosthetic leg, markers were placed on anatomic locations parallel to those on the intact leg. The kinematic and ground reaction force data were collected at 60 and 1200Hz, respectively.

Protocol

Subjects were asked to walk at their self-selected speeds along the forceplate walkway. A successful step was one in which each foot landed directly on the forceplates. A minimum of 4 gait cycles (from heel strike to heel strike) was collected for both the intact and residual legs during each data collection session. Trials for each patient were analyzed with respect to one another to check for consistency in kinesiologic measures (eg, walking speed, cadence, stride length) and to ensure that subjects were walking with a steady-state pattern.

Data Processing and Analysis

The kinematic and ground reaction force data were filtered with a fourth-order zero-phase shift low-pass Butterworth filter with cutoff frequencies of 6 and 20Hz, respectively. The corresponding kinematic derivatives were computed using a generalized, cross-validation spline algorithm,¹⁵ and the ground reaction forces were normalized to body weight. Walking speed and cadence, residual- and intact-leg peak AP ground reaction forces, step length, stance time, and gait cycle time were determined for each foot-ankle combination. The corresponding braking and propulsive impulses were determined for each leg by integrating the negative and positive areas under the ground reaction force curves, respectively, over the gait

Table 1: Kinematic and Temporal Parameters for Subjects While Wearing the 4 Foot-Ankle Prosthesis Combinations

Prosthesis Combinations	Walking Speed (m/s)	Cadence (steps/min)	Residual-Leg Gait Cycle Time (s)	Intact-Leg Gait Cycle Time (s)	Residual-Leg Step Length (m)	Intact-Leg Step Length (m)
SACH	1.04±0.15	104.0±9.2	1.16±0.11	1.16±0.10	0.63±0.08	0.57±0.06
SACH-MA	1.03±0.15	103.7±8.6	1.17±0.10	1.17±0.10	0.63±0.08	0.57±0.06
CCII	1.02±0.15	102.8±9.7	1.17±0.12	1.18±0.12	0.62±0.08	0.57±0.06
CCII-MA	1.02±0.15	103.3±6.7	1.16±0.08	1.17±0.08	0.62±0.08	0.57±0.08

NOTE. Values are average ± standard deviation (SD). There were no significant changes in walking speed, cadence, residual-leg step length, or intact-leg step length as a result of the different foot-ankle combinations. The residual-leg step length was significantly greater than the intact-leg step length for all 4 foot-ankle combinations ($P<.01$).

cycle. The residual-to-intact-leg ratios for braking and propulsive impulses were computed to evaluate leg-loading symmetry.

The braking and propulsive impulses and the corresponding peak ground reaction forces and impulse duration (percentage of the gait cycle) were statistically compared when subjects wore each of the 4 foot-ankle combinations. Repeated-measures multivariate analyses of variance were used to determine if there was a significant foot (SACH or CCII), ankle (with or without the multi-axis ankle), or foot-ankle interaction effect on the various walking parameters on each leg. When significant effects were detected, a univariate analysis with a Bonferroni adjustment was used to determine which changes were statistically significant ($P<.05$). Because the residual and intact legs were tested separately, walking parameters were also compared between legs to determine the relation between the residual and intact legs and if that relation was affected by the prosthesis components. Paired t tests with a Bonferroni adjustment were used to determine statistically significant differences in the walking parameters between the residual and intact legs ($P<.01$).

RESULTS

Temporal Parameters

There were no significant differences in the temporal and kinematic variables including walking speed, cadence, and residual- or intact-leg gait cycle time and step length when subjects wore the different foot-ankle combinations (table 1). However, for all foot-ankle combinations, the residual-leg step length was significantly greater than intact-leg step length ($P<.01$).

Ground Reaction Force Impulses

Residual-to-intact-leg comparison. There were significant differences in the braking and propulsive impulses generated by the residual and intact legs (table 2). The intact leg gener-

ated a significantly greater propulsive impulse than the residual leg for all foot-ankle combinations ($P<.01$). In addition, the braking impulse generated by the intact leg was significantly greater than the residual leg when amputees wore the CCII-MA prosthesis ($P=.004$).

Influence of foot-ankle components. The addition of the multi-axis ankle significantly increased the residual-leg propulsive impulse ($F_{1,14}=13.188$, $P=.003$) (see table 2). However, neither the prosthetic foot nor foot-ankle interaction had a significant effect on residual-leg propulsive impulse, nor was there a significant change in residual-leg braking impulse when subjects wore any of the foot-ankle combinations. Thus, our hypothesis that ESAR feet and multi-axis ankles improve the ability of the residual leg to generate braking and propulsive impulses was only partially supported. In addition, there was no significant change in the intact-leg braking or propulsive impulse when subjects wore any of the foot-ankle combinations.

Residual-to-Intact-Leg Impulse Ratio

The residual-to-intact-leg braking and propulsive impulse ratios were below 1 for all foot-ankle combinations (ie, the intact-leg impulses were always greater than those of the residual leg). The residual-to-intact-leg propulsive impulse ratio increased when using a multi-axis ankle with either foot (see table 2). The prosthetic foot did not have an effect on either the braking or propulsive impulse ratio. However, the CCII-MA prosthesis produced a noticeably lower braking impulse ratio than the other prostheses. The SACH-MA prosthesis produced the average braking and propulsive impulse ratio closest to 1.

Peak Ground Reaction Forces

For all 4 foot-ankle combinations, the intact leg generated significantly greater peak braking and propulsive AP ground reaction forces ($P<.01$) (table 3). There were no significant changes in any of the peak AP ground reaction forces on the

Table 2: Braking and Propulsive Impulses of the Residual and Intact Legs While Wearing the 4 Foot-Ankle Combinations

Prosthesis Combinations	Residual-Leg Impulse (% body weight · s)		Intact-Leg Impulse (% body weight · s)		Residual-to-Intact Ratio	
	Braking	Propulsion	Braking	Propulsion	Braking	Propulsion
SACH	-2.27±0.74	1.71±0.49	-2.44±0.55	2.79±0.56 [†]	0.98±0.43	0.61±0.14
SACH-MA	-2.34±0.95	2.00±0.51*	-2.63±0.54	2.71±0.75 [†]	0.93±0.49	0.78±0.21
CCII	-2.14±0.66	1.76±0.51	-2.29±0.54	2.79±0.67 [†]	0.97±0.36	0.65±0.20
CCII-MA	-1.97±0.80	2.05±0.59*	-2.57±0.59 [†]	2.72±0.63 [†]	0.76±0.33	0.79±0.29

NOTE. Values are average ± SD.

*A significant multi-axis ankle effect on the impulse measures.

[†]The intact-leg braking (propulsive) impulse differed significantly from the corresponding braking (propulsive) impulse on the residual leg for that foot-ankle combination.

Table 3: Peak AP Ground Reaction Forces on the Residual and Intact Legs for All 4 Foot-Ankle Combinations

Prosthesis Combinations	Peak Forces (% body weight) – Residual Leg	
	Braking	Propulsion
SACH	-10.39±3.04	9.86±3.08
SACH-MA	-10.91±3.93	10.58±2.45
CCII	-10.70±3.28	9.48±2.39
CCII-MA	-9.75±3.91	9.99±3.02
Prosthesis Combinations	Peak Forces (% body weight) – Intact Leg	
	Braking	Propulsion
SACH	-14.82±3.30*	13.75±2.72*
SACH-MA	-15.40±3.94*	13.17±3.75*
CCII	-13.21±2.92*	13.42±3.06*
CCII-MA	-14.47±3.84*	13.22±3.01*

NOTE. Values are average ± SD.

*The intact leg differed significantly from the corresponding measure on the residual leg for that foot-ankle combination.

intact or residual leg as a result of the prosthetic foot, ankle, or foot-ankle interaction (see table 3).

Braking and Propulsion Duration

Residual-intact-leg comparison. When wearing the SACH, SACH-MA, and CCII-MA, subjects spent a significantly greater portion of the gait cycle in stance on the intact leg than on the residual leg ($P=.01$) (table 4). The intact leg spent significantly less time in braking and more time in propulsion when subjects wore the SACH or CCII prostheses ($P=.01$) (see table 4).

Influence of foot-ankle components. On the residual leg, there was a trend for decreased braking and increased propulsion duration when subjects wore the multi-axis ankle. This trend approached but did not reach statistical significance for either the duration of braking ($F_{1,14}=4.379$, $P=.055$) or propulsion ($F_{1,14}=4.098$, $P=.062$). There was no change in the braking and propulsion impulse duration due to the prosthetic foot or foot-ankle interactions. There were no changes in the duration of braking or propulsion in the intact leg due to the prosthetic foot, ankle, or foot-ankle interaction.

DISCUSSION

Selecting the proper prosthesis components for an amputee is an important component of a successful rehabilitation. Amputee gait is often characterized by asymmetric kinematics and leg loading, with increased leg loading on the intact leg often leading to the development of additional musculoskeletal disorders.^{4,7,8} The goal of the present study was to examine the braking and propulsive impulses on both the intact and residual legs while amputees wore 2 different prosthetic feet with and without a multi-axis ankle to gain insight into the influence of individual components on impulse generation. We also examined changes in peak AP ground reaction forces and the duration of braking and propulsion to determine the cause of any changes in the corresponding impulses.

The analysis showed no statistically significant changes in walking speed, cadence, and residual- or intact-leg gait cycle time and step length when subjects used any of the 4 foot-ankle prostheses (see table 1). These results were consistent with previous studies^{9,11,13,16,17} comparing the biomechanical performance of ESAR feet versus conventional non-ESAR feet (eg SACH), which did not find significant changes in walking speed or cadence. Similarly, other studies^{13,18} have reported no

difference in residual-leg step length with different prostheses. Previous studies^{10,18,19} have also observed a significantly greater step length in the residual leg relative to the intact leg. Contrary to our results, MacFarlane et al²⁰ observed an increased intact-leg step length when amputees wore an ESAR foot compared with a non-ESAR foot and suggested that this change was the result of amputees spending more time in single support with the residual leg because of increased stability provided by the ESAR feet. However, an important difference between that study and ours is that their subjects were younger, traumatic amputees who walked with an increased velocity relative to our subjects, who were all older, vascular amputees. In addition, a recent comparison²¹ of the SACH foot with a multi-axis Greissinger Plus foot-ankle prosthesis^e found significant increases in walking speed and cadence when amputees wore the Greissinger prosthesis, whereas our study found no difference between the feet analyzed. However, those participants were also traumatic amputees who were less than 1 year removed from amputation and thus were in the early stages of rehabilitation. Vascular amputees exhibit decreased walking velocity, stride length, and other gait parameters relative to traumatic amputees.²

Effectively generating propulsive impulses from both legs is important to maintain a given walking speed, produce a symmetric gait pattern and balance limb loading. The data showed that the addition of a multi-axis ankle produced a significant increase in the residual-leg propulsive impulse (see table 2). However, there was no significant change in the peak residual-leg propulsive ground reaction force or the impulse duration due to the prosthetic foot, ankle, or foot-ankle interactions (see tables 3, 4). The increased residual-leg propulsive impulse appears to be the result of a combined trend for both the peak force and impulse duration to increase when using the multi-axis ankle, with the increased impulse duration approaching significance ($P=.062$). Thus, subjects were able to increase their residual-leg propulsive impulses when wearing multi-axis ankles primarily by increasing the propulsive ground reaction force duration but also by increasing the propulsive ground reaction force magnitude (fig 1).

Braking and propulsive impulses for 3 active, adult, male transtibial amputees walking with a SACH, Seattle (an energy storage and return foot), and Jaipur (a prosthetic foot created to

Table 4: Duration (percentage of gait cycle) of Braking, Propulsion, and Stance for the Residual and Intact Legs With the 4 Foot-Ankle Combinations

Prosthesis Combinations	Stance Phase Braking and Propulsion (% GC) – Residual Leg		
	Braking	Propulsion	Stance
SACH	35.25±7.26	28.74±6.09	63.99±3.19
SACH-MA	33.41±8.90	30.91±7.67	64.31±2.88
CCII	35.73±4.09	28.88±4.32	64.61±3.28
CCII-MA	32.67±6.29	32.05±6.16	64.72±2.59
Prosthesis Combinations	Stance Phase Braking and Propulsion (% GC) – Intact Leg		
	Braking	Propulsion	Stance
SACH	32.41±3.96*	33.97±3.58*	66.38±1.90*
SACH-MA	33.69±5.04	33.63±4.27	67.31±2.33*
CCII	30.93±3.74*	34.69±3.82*	65.62±2.80
CCII-MA	32.41±3.90	34.83±4.02	67.24±2.67*

NOTE. Values are average ± SD.

Abbreviation: GC, gait cycle.

*The intact leg differed significantly from the corresponding measure on the residual leg for that foot-ankle combination.

meet the cultural and socioeconomic needs of amputees in India) foot have been previously reported by Arya et al.¹² The braking impulses for the Seattle and SACH feet were 2.94% and 2.88% body weight per second (scaled from N·s/kg), respectively, and their propulsive impulse results were 2.78% and 2.83% body weight per second (scaled from N·s/kg), respectively. These residual-leg braking and propulsive impulses were slightly higher than our values, which could be the result of different walking speeds tested (not reported in their study). However, their results were consistent with our data in that the residual leg produced a greater braking than propulsive impulse and in that there was little difference in the braking or propulsive impulses between the SACH and Seattle (ESAR) feet.

The residual-to-intact-leg braking and propulsive impulse ratios were used to assess the relative loading symmetry between the residual and intact legs. The residual-to-intact-leg propulsive impulse ratio increased (ie, the residual leg generated a greater propulsive impulse and symmetry was improved) with the addition of multi-axis ankles (see table 2). The SACH-MA produced the best combination of residual-to-intact-leg braking and propulsive ratios (ie, the average braking and propulsion ratio was the highest, at .86) (see table 2). After testing completion, each subject was allowed to keep the foot-ankle prosthesis they most preferred. Eleven of the 15 subjects preferred the SACH-MA. Three others preferred the CCII-MA, while 1 preferred the SACH. These results suggest that patient preference may be related to loading symmetry and the ability to generate increased propulsion with the residual leg with the multi-axis ankles.

A potential limitation of this study is that we focused on a population consisting solely of older vascular amputees. Future work should be directed toward identifying whether similar benefits are observed in younger, traumatic amputees, because they may be better suited to take advantage of the increased

ankle ROM and energy storage features of ESAR feet. In addition, this study only evaluated biomechanical measures without measuring the corresponding metabolic cost. The effect of ESAR feet on metabolic cost has varied between studies (see Hafner et al.² for review), and it is not clear what effect multi-axis ankles will have on metabolic energy expenditure.

CONCLUSIONS

Our results show that the addition of multi-axis ankles to prosthetic feet improves the ability of amputees to generate propulsive impulses with the residual leg and thereby helps improve the loading symmetry between the residual and intact legs. The results also suggest that older, vascular amputees may not benefit from the increased energy storage and return provided by ESAR feet but do benefit from the increased flexibility provided by multi-axis ankles. Fourteen of the 15 subjects preferred a prosthesis with a multi-axis ankle, and 11 of the 15 subjects preferred the prosthesis that best improved the loading symmetry between the residual and intact legs. These results provide some scientific rationale for prescribing multi-axis ankles to improve amputee gait performance.

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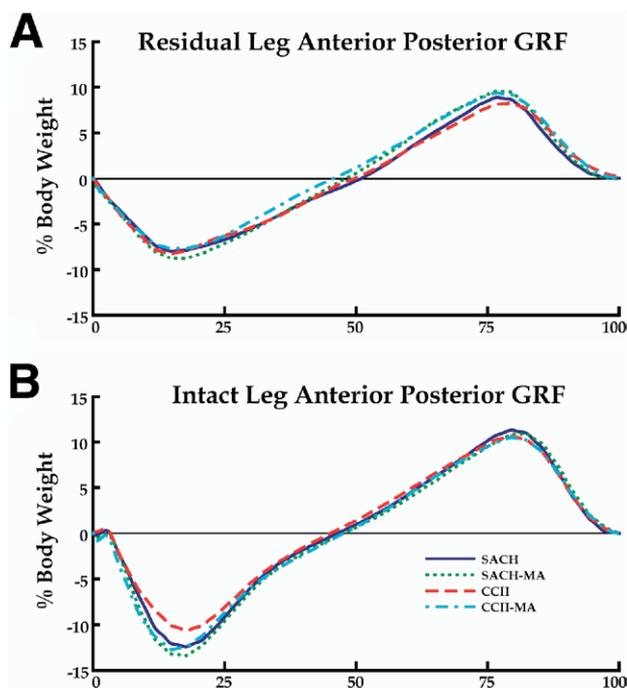


Fig 1. Group average residual- and intact-leg AP ground reaction force patterns (GRF) for the 4 foot-ankle combinations.

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Suppliers

- a. Ohio Willow Wood, 15441 Scioto-Darby Rd, Mt Sterling, OH 43143.
- b. Cyma Corp, 6405 218th St SW, Ste 100, Mountlake Terrace, WA 98043.
- c. Vicon Peak, 14 Minns Business Park, West Way, Oxford OX2 0JB, UK.
- d. Advanced Mechanical Technology Inc, 176 Waltham St, Watertown, MA 02472.
- e. Otto Bock HealthCare GmbH, Max-Näder-Str 15, 37115 Duderstadt, Germany.