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Stiffness and energy storage characteristics of energy storage and return prosthetic feet

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Thesis

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in Engineering

The University of Texas at Austin
August 2017

Acknowledgements

I would like to thank my advisor, Dr. Richard Neptune, for his advice and encouragement throughout my graduate studies. His support and guidance have been instrumental in my growth as a researcher and engineer, and I am grateful to have had the opportunity to learn so much from him. Many thanks also to Dr. Glenn Klute and Ava Segal for facilitating the collection of these data and for feedback and insight during the preparation of my thesis. My fellow members of the Neuromuscular Biomechanics Laboratory have not only been an excellent resource during my studies and research, but also the friendliest and most supportive peers I could have hoped to work beside. I would also like to thank all my family and friends, especially my parents and my fiancée, for their support throughout this process. Their support gives me the confidence to confront any obstacle. Finally, I would like to acknowledge the Department of Veterans Affairs, which funded this work.

Abstract

Stiffness and energy storage profiles of energy storage and return prosthetic feet

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Prosthetists currently lack quantifiable measures to guide prosthesis prescriptions and must rely on experience and manufacturer recommendations. Studies have shown that stiffness and energy storage characteristics of prosthetic feet significantly influence amputee gait. Consequently, several studies have attempted measure these mechanical characteristics, but typically measure only a few orientations in a single plane. This study examined the stiffness and energy storage characteristics of several prostheses over normal gait orientations with the goal of improving prosthesis prescriptions. Feet from five different manufacturers were tested with twenty-five different combinations of foot style, stiffness category and heel wedge inclusion. Force-displacement data were collected at fifteen sagittal orientations and five coronal orientations, and were used to calculate stiffness and energy storage. Loading conditions at each sagittal orientation were determined using a representative amputee's scaled walking data. Stiffness and energy storage were found to be highly non-linear in both the sagittal and coronal planes. Across all feet, stiffness was greatest near foot flat in the sagittal plane. Generally, stiffness decreased with greater heel, forefoot, medial and lateral loading orientations. Energy storage was greatest for forefoot loading and increased with medial or lateral loading orientations. As stiffness category increased within a foot style, stiffness increased and energy stored decreased. However, the recommended weight for a given foot was not linearly related to stiffness or energy storage. In addition, feet with similar manufacturer recommended weight ranges had varied energy storage over all orientations and varied stiffness over heel and foot flat loading orientations. Inclusion of heel wedges increased stiffness and decreased energy storage over heel and foot flat loading for the Vari-Flex with EVO foot, but not the Sierra foot. These results may help improve clinical prescriptions by providing prosthetists with quantitative measures to compare feet.

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Introduction

Over six hundred thousand people in the United States are living with major lower limb loss (Ziegler-Graham et al., 2008). Prosthetic feet are commonly prescribed to restore mobility and improve quality of life for lower limb amputees. Prosthetic feet help facilitate a more natural gait by attempting to emulate the biomechanical functions normally provided by the anatomical foot-ankle such as body support, propulsion and stability during stance. However, there is a lack of consensus from both researchers (Czerniecki, 2005; Hofstad et al., 2004) and clinicians (Association, 2010; Stark, 2005) on the criteria needed to inform the prescription process, which is often guided by limited manufacturer recommendations (e.g., patient weight and intended activity level).

Due to the lack of quantifiable data guiding prosthetic foot prescriptions, clinicians often rely on personal experience and empirical evidence when making prescription decisions (Menard et al., 1992; van der Linde et al., 2004). As a result, prosthetists often prescribe a small selection of feet (Stark, 2005), which may not be optimal for the patient. Previous research has sought to better inform prescriptions by developing a prosthetic foot emulator that allows patients to try more feet (Caputo et al., 2015) or by examining how different foot properties affect walking performance (Barth et al., 1992; Cortes et al., 1997; Gard, 2006; Klodd et al., 2010b; Zmitrewicz et al., 2006). However, additional quantitative information on the mechanical properties of prosthetic feet is needed to develop criteria that could help clinicians make more informed decisions.

Both stiffness (Adamczyk et al., 2017; Fey et al., 2011; Major et al., 2014; Raschke et al., 2015; Zelik et al., 2011) and energy storage and return (Casillas et al., 1995; Postema et al., 1997; Ventura et al., 2011) properties have been shown to have a significant influence on amputee gait. As a result, a number of studies have attempted to quantify prosthetic foot stiffness (Beck et al., 2016; Geil, 2001; Mason et al., 2011; van Jaarsveld et al., 1990;

Webber and Kaufman, 2016) or energy storage properties (Beck et al., 2016; Geil, 2001; Klute et al., 2004; van Jaarsveld et al., 1990; Webber and Kaufman, 2016) (for review, see Major et al., 2012). These studies often make measurements for a few conditions; either loading the prosthetic heel to simulate heel strike or the forefoot keel to simulate toe off. Others have tested feet at additional sagittal-plane angles (South et al., 2010; van Jaarsveld et al., 1990) but did not vary the coronal-plane angle, thus limiting data to a single plane. In addition, studies often make measurements at different ranges of force to calculate stiffness, which makes comparisons across studies difficult. For example, some have used a specific region of the force-displacement curve to calculate an instantaneous stiffness (Webber and Kaufman, 2016) while others have used the entire force-displacement curve to calculate a mean stiffness (Beck et al., 2016; Geil, 2001; South et al., 2010; van Jaarsveld et al., 1990). Because the stiffness properties of a prosthetic foot are most likely non-linear across the force-displacement curve, using different conditions to determine foot stiffness will likely lead to inconsistencies between studies.

The ability to make direct comparisons of the mechanical properties between various feet is necessary if these properties are to inform the clinician's prescription decisions. Standardization of testing procedures would eliminate methodologic differences that prevent comparison between studies. Although not recommended as a prescription guide, the current testing standards for lower limb prostheses (Association, 2010; ISO, 2016) only specify linear stiffness testing at a few orientations (i.e., heel contact, toe contact and foot flat for the American Orthotic and Prosthetic Association (AOPA) protocol and heel strike and toe off for International Organization for Standardization (ISO) 10328). Such limited testing does not capture the potential non-linear stiffness properties of prosthetic feet and makes comparisons across feet challenging.

The purpose of this study was to quantify the stiffness and energy storage properties of a variety of commonly prescribed prosthetic feet over the range of loading conditions and limb orientations normally experienced during amputee gait. The outcomes of this study will provide a more complete characterization of mechanical properties and allow for quantitative comparisons between feet to help inform clinical prescription decisions.

Methods

FEET TESTED

Several foot styles from five different manufacturers were tested (Table 1). At least two different stiffness categories for each foot style were tested. All feet were size 27. The stiffness categories tested ranged from two to nine. The College Park TruStep was an exception as each foot component was given a general manufacturer rating (e.g. soft, firm, extra firm) rather than a numeric one. A compliant, moderate and stiff set of components were used for the three TruStep feet tested. Two category 6 feet (Ossur Vari-Flex with EVO, Freedom Innovations Sierra) were tested both with and without optional heel wedges. The Ossur foot was tested with three different sizes of heel wedges while the Freedom Innovations foot was tested with one heel wedge. This resulted in twenty-five different combinations of foot style, stiffness category and inclusion of heel wedges being tested.

Table 1. Commercial feet tested. The conditions tested for each style of foot (stiffness category and whether a heel wedge was included) are indicated.

Manufacturer	Foot Style	Stiffness Categories	Heel Wedge
College Park	TruStep	Compliant, Moderate, Stiff	No
Freedom Innovations	Sierra	4,6,8	Yes (cat. 6)
Ossur	Sure-Flex	2,4,6	No
Ossur	Vari-Flex w/ EVO	4,5,6,7,8,9	Yes (cat. 6)
Ottobock	Trias$^+$	2,3	No
Trulife	Seattle Catalyst 9	4,6	No
Trulife	Seattle Lightfoot^2	6,8	No

EXPERIMENTAL SETUP

To determine the mechanical properties of the feet, a Kistler force plate (Kistler Instrument Corporation; Amherst, NY) rigidly mounted on an R-2000 Rotopod (Parallel Robotics System Corporation; Hampton, NH) was used to collect the force-displacement data. The R-2000 is a six-degree of freedom parallel robot with a horizontal mobile platform that allows translation and rotation in three directions.

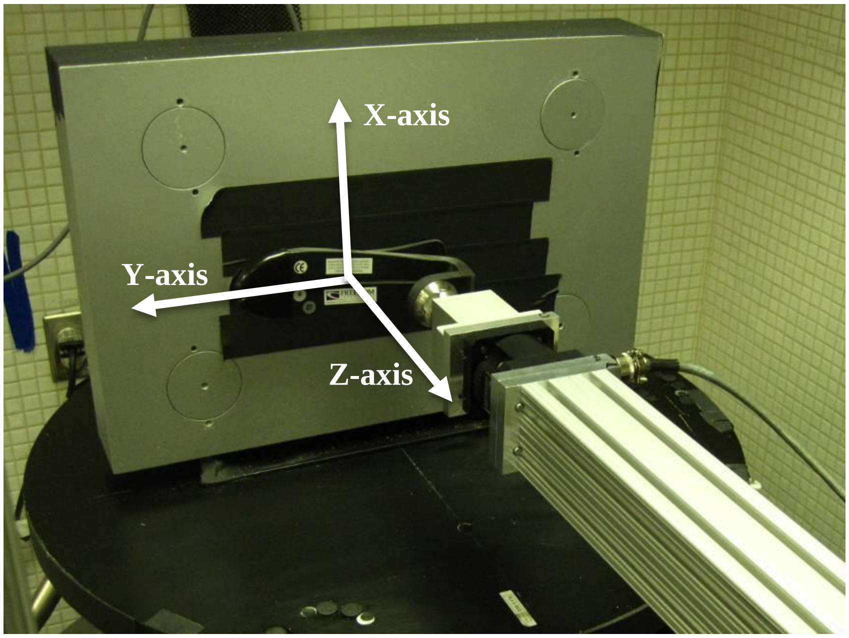

Figure 1. **Experimental setup.** When the force plate was in a foot flat orientation, the local coordinate systems of the force plate and prosthetic foot were aligned. The testing orientation was defined as the relative angular orientation between coordinate systems.

A rigid fixture held the prosthetic foot to the frame of the robot. The foot was initially aligned with the force plate using a typical gait coordinate system (Fig. 1). Relative to the force plate in a foot flat orientation without a cosmesis (0° orientation in both the sagittal and coronal planes), the X-axis was oriented in the medial-lateral direction, the Y-axis was oriented in the anterior-posterior direction and the Z-axis was orientated in the vertical direction. The sagittal-plane orientations were defined as the angular difference between the prosthetic foot and force plate about the X-axis, where negative angles correspond to heel loaded orientations and positive angles correspond to forefoot loaded orientations. The coronal-plane orientations were defined as the difference between the prosthetic foot and force plate about the Y-axis, where negative angles correspond to loading of the lateral side of the foot while positive angles correspond to medial loading. All feet were tested with the appropriate manufacturer-recommended cosmesis in place.

By altering the configuration of the Rotopod, the force plate orientation relative to the prosthetic foot could be changed. Fifteen sagittal (-15° to 30°) and five coronal (-10° to 10°) orientations were tested, yielding a total of 75 foot orientation combinations to be tested for each foot. Each test began by rotating the Rotopod and force plate to the desired orientation. The force plate was then translated along the z-axis to load the foot. Each foot was loaded at a rate of 5 mm/sec while the force-displacement data was collected at 250 Hz.

The testing load for each orientation was determined using previously collected straight line walking data from a representative amputee subject. The representative subject was chosen based on body mass, walking speed, ground reaction forces (GRFs) and pylon-ground angles. When compared with a group of transtibial subjects for these metrics, the representative subject's data fell near the group mean and thus was determined to be a representative subject. The kinetic and kinematic data from this subject was used to determine the vertical GRF at each sagittal orientation during the stance phase. The vertical GRF data were scaled to represent the group mean body mass (88.2 kg), as well as one group standard deviation (11.0 kg) above and below the group mean. For each configuration, the sagittal orientation being tested determined the maximum load applied (i.e., one standard deviation greater than the mean force value at each orientation). The range of coronal angles tested were determined from the same subject's pylon-ground angles during a one meter radius circle turning trial (methods described in (Segal et al., 2011)). The corresponding sagittal load was applied for each sagittal-coronal angle combination as the Rotopod was positioned to the desired sagittal and coronal angle, then moved along the axis of the pylon to load the foot and obtain corresponding the force-displacement data.

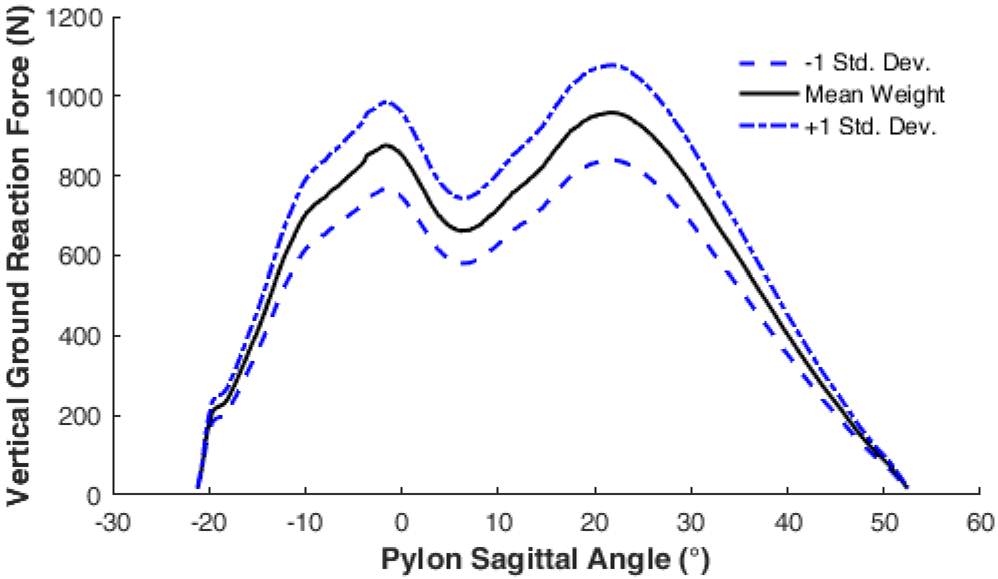

Figure 2. Vertical ground reaction force used for testing at each pylon sagittal angle orientation. The ground reaction forces for the mean group mass (88.2 kg), as well as one standard deviation below (77.2 kg) and one standard deviation above (99.2 kg) are shown.

METRICS

A functional foot stiffness metric was calculated using a simple linear regression model over the functional load range (i.e., ± one standard deviation of the mean ground reaction force) for each sagittal angle being tested. The functional stiffness at that orientation was determined as the slope of the regression model. When a test yielded a coefficient of determination below 0.99 for the functional load range, the test was repeated.

The total energy stored in the foot was calculated by trapezoidal integration of the force-displacement data over the functional load range. The foot was considered engaged with the force plate once a 20 N threshold was achieved. Thus, the energy storage integration was only performed between the lower limit of 20 N to the upper limit of the load tested.

Normalized stiffness and energy storage metrics were calculated to compare the effects of orientation on stiffness and energy storage across feet. The relative stiffness was calculated using the ratio from two orientations: a reference orientation (0° sagittal, 0° coronal) and the orientation of interest. This provides a unitless metric that describes the relative stiffness or energy storage of the foot at the orientation of interest compared to the reference orientation. Metric values less than one indicate the reference orientation is stiffer or stores more energy, while values greater than one indicate less stiffness or less energy stored. This metric provides a sense of the stiffness or energy storage profile without visually seeing the profile.

Simple linear regressions were used to model the relationship between recommended weight and stiffness or energy storage for the four foot styles with at least three stiffness categories. The slope of the fit (β) and the coefficient of determination (r^2) were determined for each sagittal orientation.

Results

The stiffness and energy storage profiles were non-linear in both the sagittal and coronal planes (Figs. 3 and 4). Although each foot possessed unique stiffness and energy storage profiles, the general shape of the profiles was similar across all feet. Overall, feet were stiffest near foot flat sagittal and neutral coronal orientations with stiffness decreasing towards more extreme sagittal or coronal orientations. Conversely, energy storage was lowest near foot flat sagittal and neutral coronal orientations with energy storage increasing towards more extreme sagittal or coronal orientations.

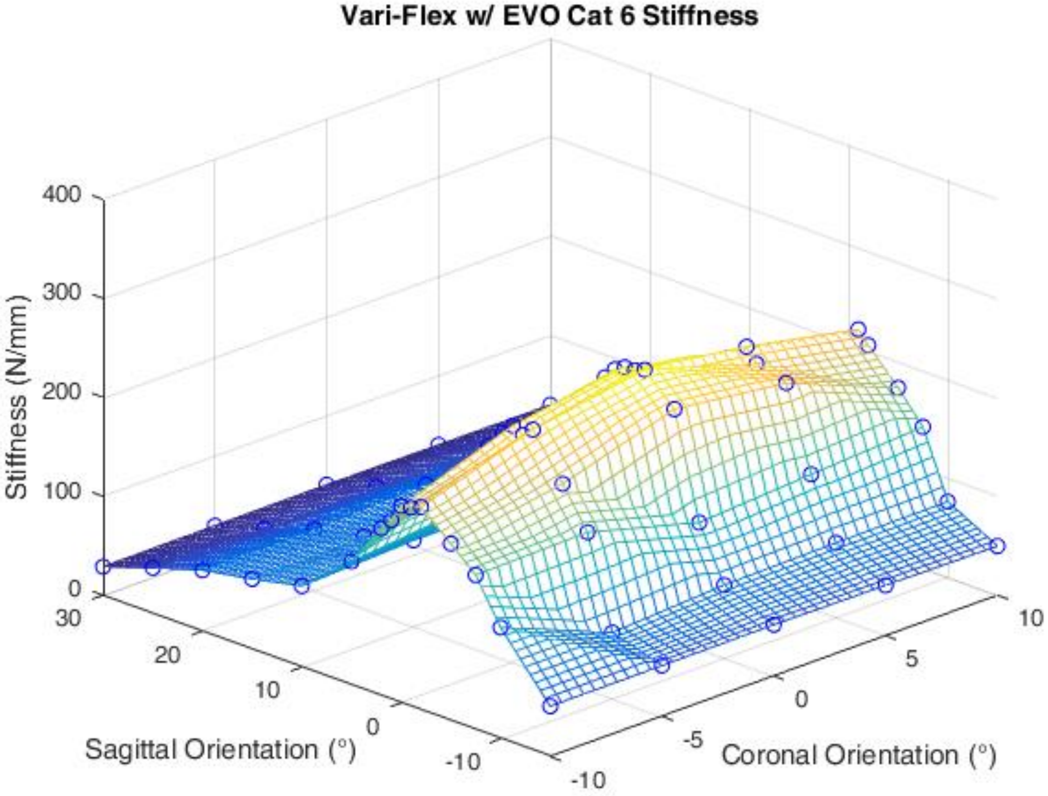

Figure 3. **Representative stiffness profile across foot orientations** (Vari-Flex with EVO, category 6). Circles indicate actual measured stiffness values. The surface was linearly interpolated between the measured data points. Positive and negative sagittal angles correspond to forefoot and heel loading, respectively. Positive and negative coronal angles correspond to medial and lateral loading, respectively.

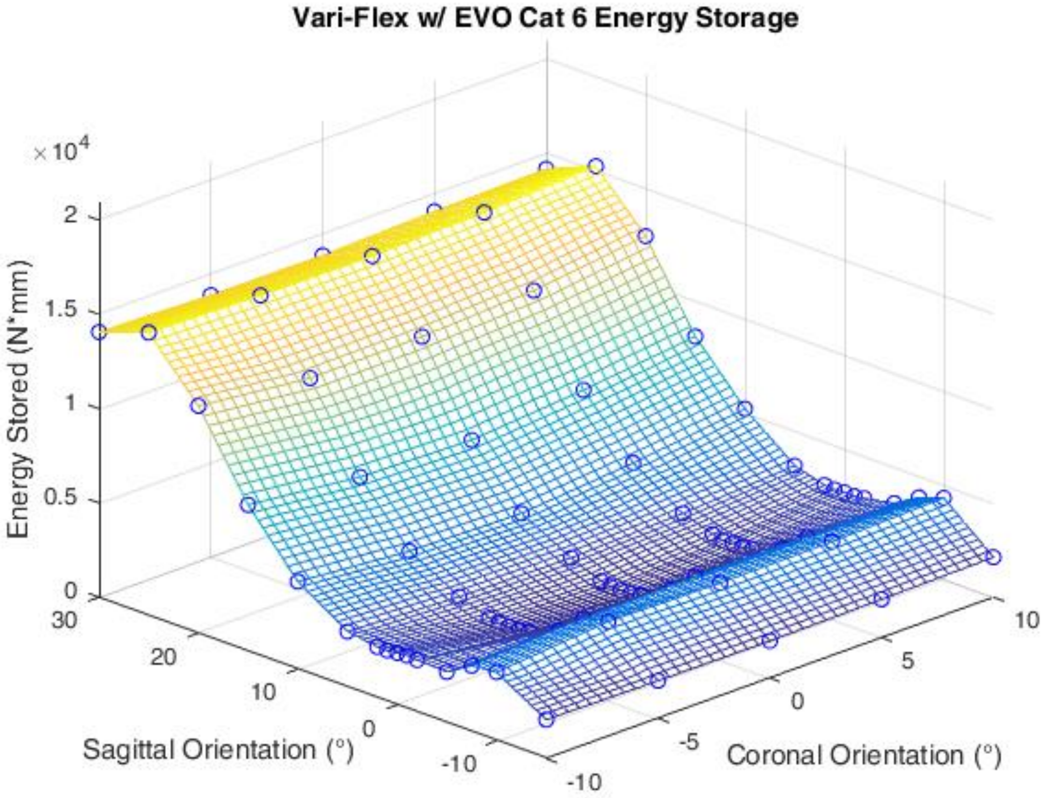

Figure 4. **Representative energy storage profile across foot orientations** (Vari-Flex with EVO, category 6). Circles indicate actual measured stiffness values. The surface was linearly interpolated between the measured data points. Positive and negative sagittal angles correspond to forefoot and heel loading, respectively. Positive and negative coronal angles correspond to medial and lateral loading, respectively.

INFLUENCE OF SAGITTAL ORIENTATIONS ON MECHANICAL PROPERTIES

Stiffness was greatest for sagittal orientations near foot flat with the maximum stiffness for all feet located between -5° and 2° (Fig. 5; Table A1). Maximum stiffness values ranged from 5.4 to 14.2 times greater than the minimum stiffness. Stiffness decreased with orientations towards heel loading or forefoot loading. All twenty feet that did not experience slippage during testing had a minimum stiffness at the greatest forefoot loading orientation (30° sagittal). Four of the five feet experiencing slippage had a minimum stiffness at the maximum heel loading orientation (-15° sagittal) while the other foot had the minimum stiffness at the greatest forefoot loading orientation it was tested at (10° sagittal). The heel strike orientation (-15° sagittal) for non-slippage feet was between 24.6% and 225.7% stiffer than the toe-off orientation (30° sagittal).

Energy storage was greatest during forefoot loading orientations, with all feet storing the most energy at sagittal orientations of either 25°, 30° or the greatest sagittal orientation tested without slippage (Fig. 6; Table A2). The least amount of energy storage occurred at either the maximum heel loading orientation (-15° sagittal) or at a sagittal orientation near foot flat (between -2° and 1°). Maximum energy storage ranged from 2.7 to 15.5 times greater than the minimum energy stored for all feet.

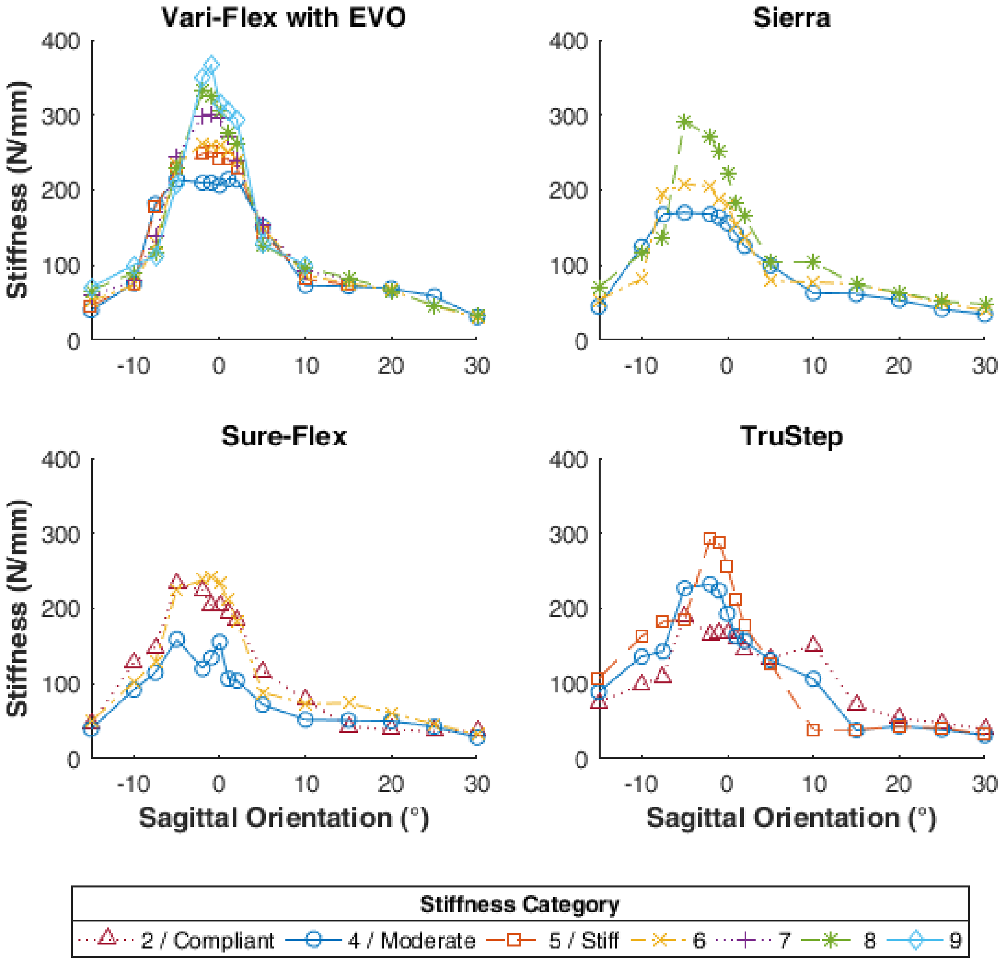

Figure 5. **Stiffness values for all feet styles with at least three stiffness categories tested.** Stiffness values are reported at a coronal orientation of 0°. Positive and negative sagittal angles correspond to forefoot and heel loading, respectively.

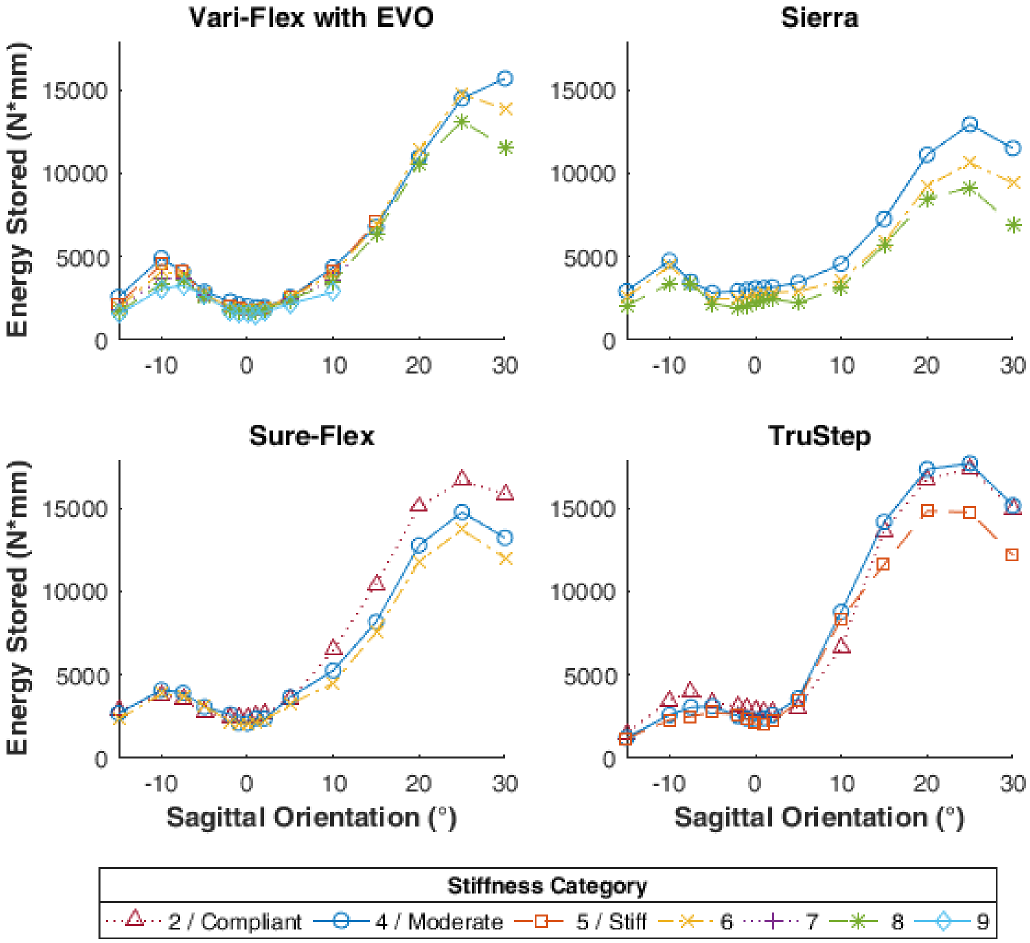

Figure 6. **Energy storage values for all feet styles with at least three stiffness categories tested.** Energy values are reported at a coronal orientation of 0°. Positive and negative sagittal angles correspond to forefoot and heel loading, respectively.

INFLUENCE OF CORONAL ORIENTATION ON MECHANICAL PROPERTIES

Overall, stiffness decreased as coronal orientation increased towards medial or lateral loading (Fig. 7). However, the influence of coronal orientation on stiffness was dependent on the foot's sagittal orientation. The 5° medial and lateral loading were on average 1.7% less stiff than the coronally neutral orientation (0°). Similarly, the 10° medial and lateral loading orientations were 7.1% less stiff than the coronally neutral orientation. Stiffness of medial or lateral loading only exceeded coronally neutral stiffness at a few sagittal orientations: -10, -7.5 and 5°. Coronal orientation had the greatest influence on stiffness near foot flat orientations (between sagittal orientations -5° and 2°). Across this range, 5° medial and lateral loading were 4.3% less stiff and 10° medial and lateral loading were 15.5% less stiff than the neutral coronal orientation.

Increased coronal orientation resulted in increased energy storage (Fig. 8). Medial or lateral loading at 5° and 10° stored 5.9% and 18.8% more energy on average than neutral coronal orientations, respectively. The influence of coronal orientation on energy storage was also dependent on the foot's sagittal orientation. Medial or lateral loading had the greatest effect on energy occurred at sagittal orientations between -2° and 10°. Over these sagittal orientations 5° medial and lateral loading stored on average 10.5% more energy than the corresponding neutral coronal orientation, while 10° medial and lateral loading stored 33.4% more energy.

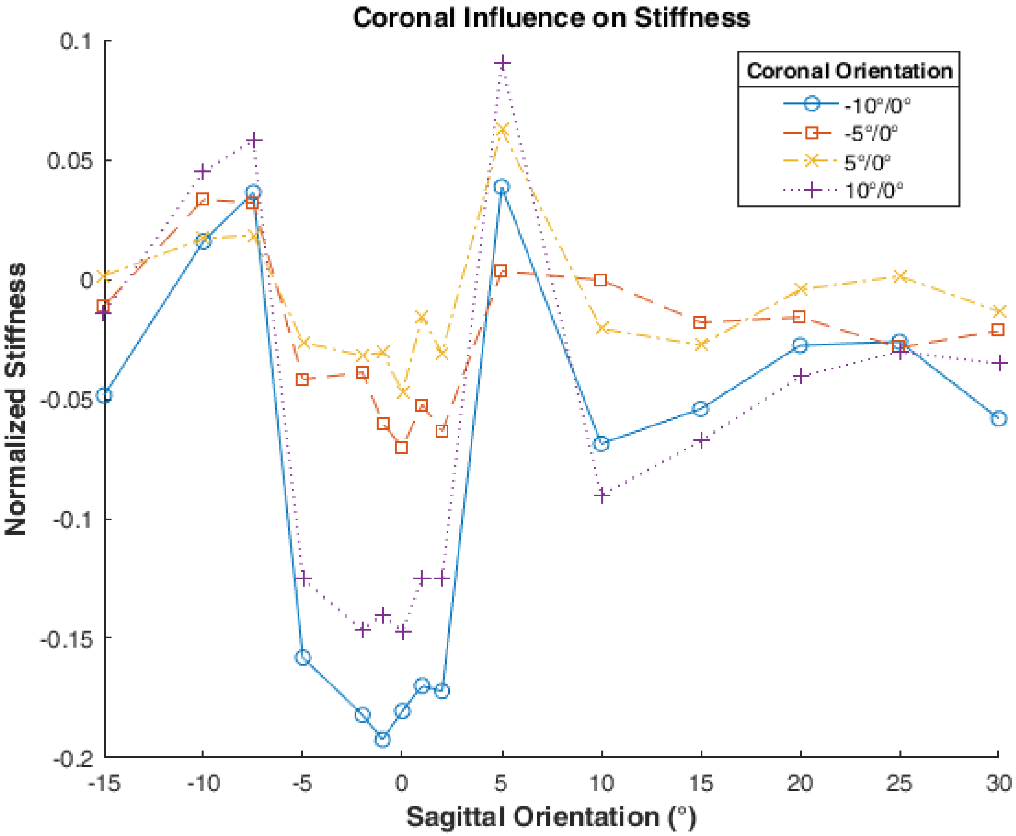

Figure 7. **Mean normalized stiffness values for all feet styles.** All normalized stiffness values were normalized by the mean stiffness at 0° in the coronal plane over all feet. Positive and negative sagittal angles correspond to forefoot loading and heel loading, respectively. Positive and negative coronal angles correspond to medial and lateral loading, respectively.

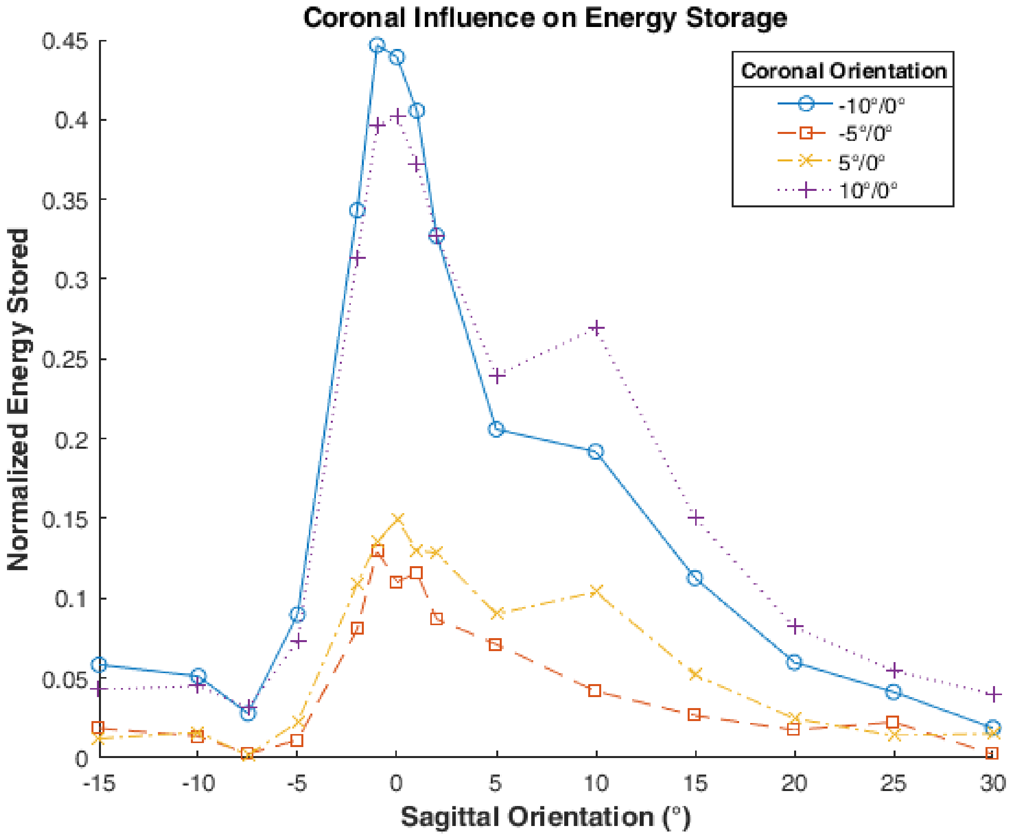

Figure 8. **Mean normalized energy stored for all feet styles**. All normalized energy storage values were normalized by the mean energy stored at 0° in the coronal plane over all feet. Positive and negative sagittal angles correspond to forefoot loading and heel loading, respectively. Positive and negative coronal angles correspond to medial and lateral loading, respectively.

INFLUENCE OF STIFFNESS CATEGORIES AND RECOMMENDED WEIGHT ON MECHANICAL PROPERTIES

The Sure-Flex foot had no significant relationships ($p<0.05$) between recommended weight, stiffness or energy storage over all orientations. The other three feet had a significant linear relationship between stiffness and mean recommended weight for 25 out of the possible 45 orientations (Table A3). Similarly, 12 out of 45 possible orientations had a significant linear relationship between energy stored and mean recommended weight (Table A4). The foot flat region (from sagittal orientations -2° to 2°) produced the most correlated stiffness and recommended weight relationships. Excluding the Sure-Flex, all foot flat orientations had a coefficient of determination (r^2) value of at least 89%, with a significant linear relationship between stiffness and recommended weight for 11 out of the 15 possible orientations.

Several of the feet tested had similar recommended weight ranges for a moderate impact level (Table A5). Three category 6 feet had a recommended weight range between 89 to 100 kg: the Vari-Flex with EVO, the Seattle Catalyst 9 and the Sierra. Similarly, the Trias+ category 2, Sure-Flex category 4 and the moderate stiffness Trustep feet all had a recommended weight between 82 to 95 kg. Despite similar weight recommendations, both groups of feet varied in stiffness over heel and foot flat orientations (sagittal orientations -5° and less) as well as energy stored over all orientations (Figs. 9 and 10). For sagittal orientations -15° to 5°, there was a mean difference in stiffness of 19.6% within the 89 to 100 kg category feet while there was a mean difference in stiffness of 27.2% within the 82 to 95 kg category feet. Although the stiffness varied over the heel loaded and forefoot orientations, there was much less variability in sagittal orientations of 15° and greater. Over these orientations the 89 to 100 kg category group differed by 4.5% on average, and the 82 to 95 kg category group differed by 6.5% on average. The energy stored over all orientations differed, on average, 15.8% and 9.0% for the 89 to 100 kg category group and the 82 to 95 kg category group, respectively.

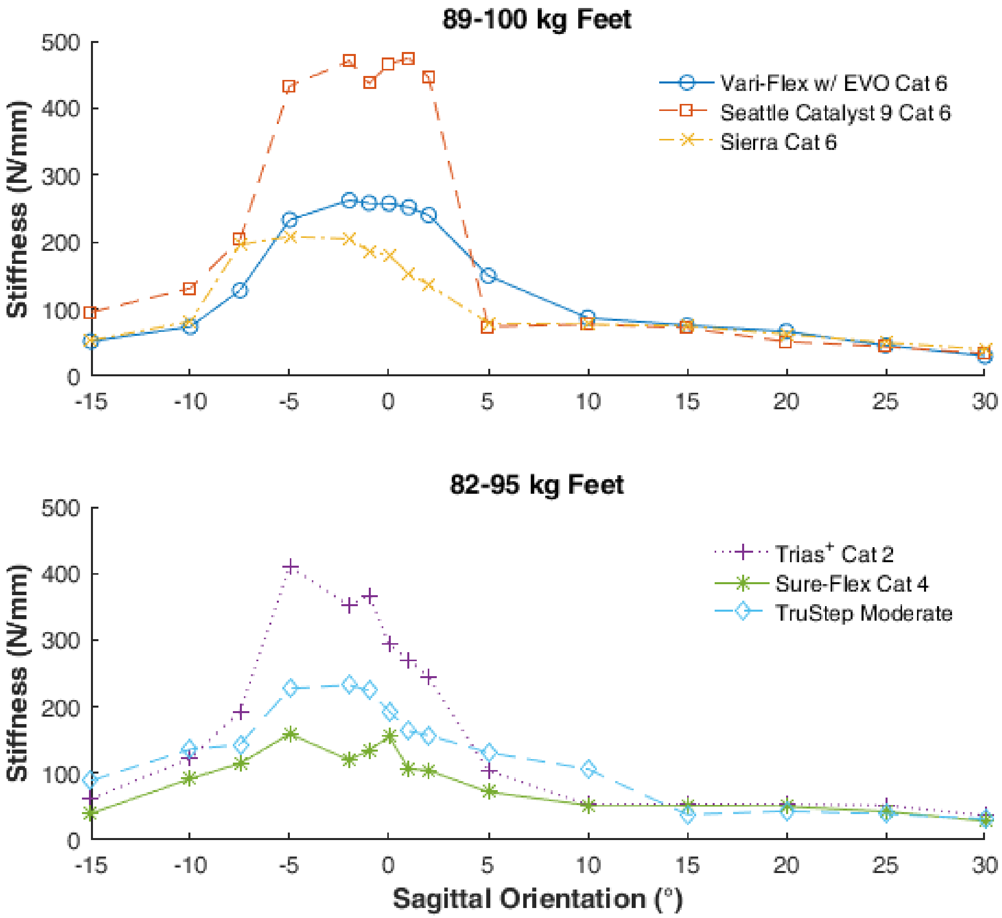

Figure 9. **Stiffness values for two different groups of feet with similar weight recommendations for a moderate impact individual**: three feet with a weight range near 89 to 100 kg (top), and three feet with a weight range near 82 to 95 kg (bottom). All stiffness values are reported at a coronal orientation of 0°. Positive and negative sagittal angles correspond to forefoot loading and heel loading, respectively.

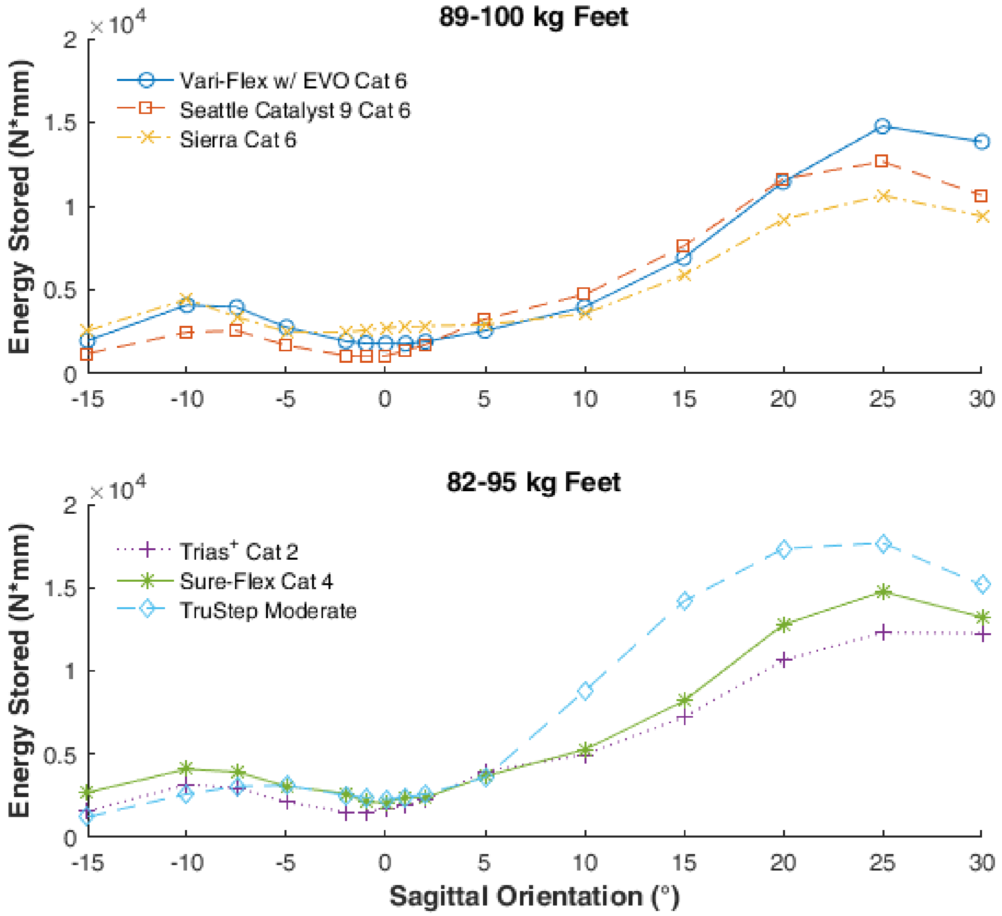

Figure 10. Energy storage values for two different feet groups with similar weight recommendations for a moderate impact individual: three feet with an approximate weight range of 89 to 100 kg (top), and three feet with an approximate weight range of 82 to 95 kg (bottom). All energy values are reported at a coronal orientation of 0°. Positive and negative sagittal angles correspond to forefoot loading and heel loading, respectively.

INFLUENCE OF HEEL WEDGE ON MECHANICAL PROPERTIES

In general, the inclusion of a heel wedge produced an increase in stiffness and a decrease in energy storage for the Vari-Flex with EVO foot (Figs. 11 and 12). The heel wedge produced the greatest increase in stiffness and decrease in energy storage over all heel loading and foot flat orientations (sagittal orientations up to 2°). Over these orientations, the mean increase in stiffness for the small, medium and large heel wedges relative to no wedge were 19.9%, 29.9% and 41.0%. The inclusion of heel wedges produce a mean decrease in energy storage over heel and foot flat orientations of 16.6%, 16.8% and 24.7% for the small, medium and large heel wedges, respectively. In contrast, the heel wedges had a much smaller effect over forefoot loading orientations (sagittal orientations from 5° to 30°). The mean deviation in stiffness for forefoot loaded orientations was -4.5%, 1.2% and 1.2% for the small, medium and large wedges, respectively. The small, medium and large wedges also produced a mean deviation in energy storage of 2.7%, 0.7% and -0.1% over the forefoot loaded orientations.

Unlike the Vari-Flex with EVO heel wedges, the Sierra heel wedge did not produce a large effect on the stiffness and energy storage over all of the sagittal orientations tested. The heel wedge produced a mean stiffness increase of 5.5% while the energy stored decreased on average 1.5%.

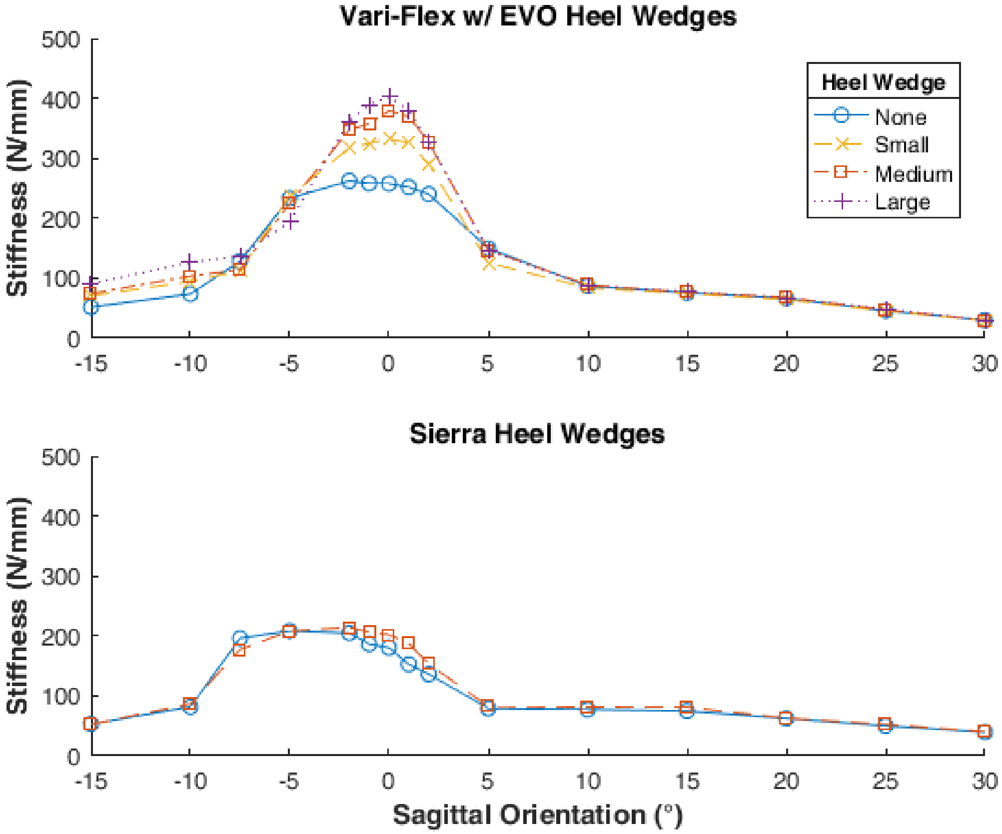

Figure 11. **Stiffness values for the heel wedge conditions**. All values are reported at a coronal orientation of 0°. Positive and negative sagittal angles correspond to forefoot loading and heel loading, respectively.

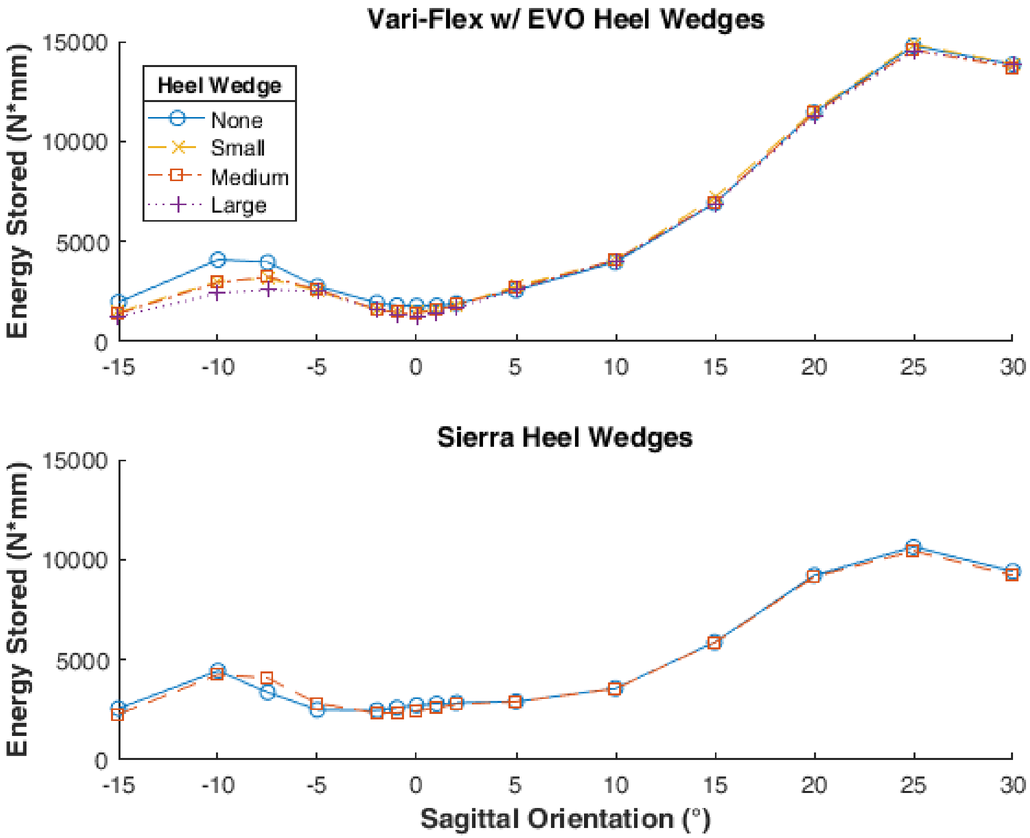

Figure 12. Energy storage values for the heel wedge conditions. All values are reported at a coronal orientation of 0°. Positive and negative sagittal angles correspond to forefoot loading and heel loading, respectively.

Discussion

This study investigated how stiffness and energy storage of prosthetic feet varies across loading orientations, stiffness category and foot style with the goal of helping to inform clinical prescription decisions. In general, the stiffness and energy storage profiles were similar for all feet and highly non-linear in both the sagittal and coronal planes.

Stiffness was greatest for orientations near foot flat, with decreased stiffness during heel loading and forefoot loading conditions (Fig. 5). The large increase in stiffness near foot flat is most likely due to the loading of both the heel and forefoot keels. For heel and forefoot loading conditions, only a single component is engaged (either the heel or forefoot keel), which results in lower stiffness values. Peak stiffness ranged from 175 N/mm to 474 N/mm which either exceeded foot flat stiffness values (South et al., 2010) or were on the high end of maximum stiffness values (van Jaarsveld et al., 1990) reported in previous studies (Table A1). In general, heel loading orientations were stiffer than forefoot loading orientations, with all heel-strike orientations (-15° sagittal) stiffer than toe-off orientations (30° sagittal) (Fig. 5; Table A1). These results were consistent with the general findings from previous studies (Mason et al., 2011; van Jaarsveld et al., 1990; Webber and Kaufman, 2016) with the exception of South et al., (2010) who found the toe-only stiffness was over twice as stiff as the heel-only stiffness.

Stiffness generally increased with stiffness category and decreased with medial or lateral loading, but there were some orientations where these trends did not hold true. Since the testing load was fixed for a given sagittal orientation for all feet, it is possible that at these trend opposing orientations the lower stiffness category feet deformed enough to engage both keels, while higher stiffness category feet reached the maximum testing load before both keels were loaded. Feet in lower stiffness categories tended to have a greater range of sagittal orientations near foot flat with high stiffness than higher category feet of the same style (Fig. 5). Thus, some of the lower category feet were stiffer than higher category feet at sagittal orientations just outside of foot flat in both heel and forefoot loading. Similarly, there were several orientations where the stiffness for medial and lateral loading exceeded that of neutral coronal orientations (Fig. 7). Similarly, it is possible that at these sagittal orientations, the medial or lateral positions were so compliant that both keels were loaded, while the neutral coronal orientation reached the maximum testing load before engaging both keels. Engagement of both keels would cause the functional stiffness of medial and lateral loading to be greater than that of the neutral coronal orientation, even though the overall stiffness (total load divided by total displacement) would still be greater for the neutral coronal position.

Energy storage and return prosthetic feet seek to emulate the function normally provided by the ankle muscles by absorbing energy in the heel during early stance for braking and returning that energy before mid-stance, and then storing energy in the forefoot keel just following mid-stance and returning that energy in late stance for forward propulsion (Fey et al., 2011; Hafner et al., 2002; Silverman and Neptune, 2012; Zelik et al., 2011; Zmitrewicz et al., 2006). The energy storage profiles show that the heel and forefoot loading orientations are able to store more energy than during foot flat, with the forefoot loading storing the most energy (Fig. 6). In general, feet of the same style with lower stiffness values store more energy, which agrees with previous findings (Fey et al., 2011, 2013; Hafner et al., 2002). However, these findings may be influenced by the force invariant testing scheme used (Adamczyk et al., 2017). The negative relationship between stiffness and energy stored did not hold across foot styles. For example, even though the TruStep with stiff components had greater forefoot and maximum stiffness values than the Sure-Flex category 6 foot, the TruStep also had the greater forefoot and maximum energy storage values (Table A1; Table A2). Future work could focus on optimizing the tradeoff between stiffness and energy storage to maximize performance.

An interesting finding was that the recommended weight (i.e., stiffness category) for the same foot style produced varying effects on the mechanical properties (Table A3; Table A4). There were inconsistent linear correlations for the mechanical properties with increasing mean recommended weight. Testing additional stiffness categories or foot styles and access to the methods used by manufactures to set recommended weight ranges would provide further insight into these relationships. However, these methods are often proprietary and not shared by manufacturers (Major et al., 2012).

Although patient weight and intended activity level are often the only manufacturer guidelines provided to prosthetists when selecting an appropriate stiffness category, these two guidelines alone do not guarantee similar mechanical properties for different feet. Stiffness and energy storage values for feet grouped according to similar recommended weight ranges for a moderate activity level were varied across all orientations (Figs. 9 and 10). Only the stiffness at forefoot loading orientations did not vary greatly across feet. A previous study found that feet recommended for the same weight and activity level could have variable heel and forefoot stiffness (Webber and Kaufman, 2016). Whereas the stiffness values for the recommended weight matched feet varied greatly over heel loading and foot flat orientations, the variability in stiffness was lower over forefoot loading orientations (Table A1). A larger range of stiffness values was found for heel loading than for forefoot loading for the weight and activity level matched feet, which is consistent with the findings of Webber and Kaufman (2016).

Another interesting finding was that the addition of heel wedges produced contrasting results for the two feet tested. Heel wedges are intended to increase the stiffness of the prosthesis during heel loading orientations. For the Vari-flex with EVO, inclusion of progressively larger heel wedges increased stiffness and decreased energy stored over the heel loading and foot flat orientations (Figs. 11 and 12). In contrast, adding a heel wedge to the Sierra foot had a minimal influence on stiffness and energy storage over all orientations. Future work is needed to test more feet and identify the design aspects that produce these contrasting results.

This study has reported generalized findings across feet, however specific comparisons between feet may be more helpful when making clinical prescription decisions. To this end, we have created a standalone graphical user interface (GUI) tool in MATLAB (The MathWorks, Inc., Natick, MA) to allow individuals to make their own comparisons. Mechanical properties of multiple feet can be compared with the GUI by plotting the stiffness and energy profiles in subplots next to one another or by using overlays in the same plot. The GUI can also generate tables of the mechanical properties for all feet with either foot style, mechanical property or orientations examined held fixed. The ability to directly compare feet may be beneficial to prosthetists by allowing them to examine feet with which that they do not have prior experience.

Potential Limitations and Future Work

Despite the inclusion of twenty-five feet in this study, testing more feet is necessary to further investigate the findings with uncertain outcomes such as the linearity of mechanical properties within a foot style and the effect of heel wedges on mechanical properties. When examining whether changes in manufacturer recommended weight correlated with stiffness or energy storage, a potential limitation of this study was only a single foot type was tested for more than three recommended weights. With the limited number of stiffness categories tested for each foot only the strongest correlations were statistically significant. Including all possible stiffness categories for a given foot style would improve the power of a linear regression across stiffness categories. This additional statistical power may help determine if the correlations between recommended weight and mechanical properties are robust across all stiffness categories. Similarly, only two feet were tested with heel wedges. With a greater sample size, more generalizations about the effect of heel wedges may be made.

Another potential limitation of this study was that loading forces were the same across all feet tested, despite variations in recommended user weight (Table A5). This allowed for direct comparisons of each foot's stiffness and energy storage for a representative amputee. However, using similar loading forces meant that stiffness or energy storage may have been under or overestimated, depending on whether the testing load was lower or higher than the recommended weight for each foot. When making prescription decisions, prosthetists may prefer to use stiffness and energy storage profiles that are scaled to their patient. This would require recalculating the stiffness and energy storage using a different maximum load and function stiffness load range. Once data has been collected, it is only possible to use force displacement data to recalculate stiffness for a patient with a lower body mass than the maximum testing load. To ensure that stiffness can be calculated for individuals of any body mass, it would be advantageous to test all feet at high loads so that the stiffness can be calculated for a greater range of patients with a single test.

While the mechanical properties determined from this study may better inform the prescription process, it is unknown how these properties might affect gait. Several studies have examined how altering stiffness influences amputee gait (Adamczyk et al., 2017; Fey et al., 2011; Klodd et al., 2010a; Raschke et al., 2015; Ventura et al., 2011). Future studies should focus on how altering mechanical properties (i.e., specific regions of stiffness or energy storage profiles) influences amputee gait. When possible, these studies should try to match commercially available feet as a baseline before systematically altering the mechanical properties (Adamczyk et al., 2017; Fey et al., 2011; Major et al., 2012).

Summary

The stiffness and energy storage of prosthetic feet were measured over orientations that are typically experienced during amputee gait. Mechanical properties were found to be highly non-linear in both the sagittal and coronal planes for all feet tested. Manufacturer recommendations for weight and activity level did not produce similar mechanical properties across foot styles. Results of this study may help inform clinical prescription decisions by providing quantitative foot characteristics to supplement prosthetist experience when comparing feet. Prosthetists may also be able to consider feet they have little experience with when making prescriptions. Future work linking mechanical properties with clinical outcomes may improve the prescription process by identifying how different aspects of prosthetic feet influence amputee gait.

Appendix

Table A1. Heel (-15° sagittal; 0° coronal), forefoot (either 30° sagittal or the greatest orientation without slippage; 0° coronal) and maximum stiffness values for all feet. The orientation of the maximum stiffness is also reported.

Feet		**Heel Stiffness (N/mm)**	**Forefoot Stiffness (N/mm)**	**Maximum Stiffness (N/mm)**	**Maximum Stiffness Location**	
Foot Style	**Stiffness Category**				**Sagittal (°)**	**Coronal (°)**
Seattle Catalyst 9	4	70.3	69.3	424.9	2	0
	6	95.4	33.6	474.4	1	0
Vari-Flex w/EVO	4	40.1	31.2	214.5	1	0
	5	45.6	73.6	250.5	-1	0
	6	51.9	30.0	262.3	-2	0
	Small Wedge	70.7	29.6	331.9	0	0
	Medium Wedge	74.2	30.2	379.4	0	0
	Large Wedge	90.7	29.8	402.5	0	0
	7	59.2	82.4	299.7	-1	0
	8	66.2	32.6	332.1	-2	0
	9	70.5	100.5	366.6	-1	0
Sierra	4	44.9	34.5	175.3	-2	-5
	6	53.2	39.8	208.4	-5	0
	Medium Wedge	52.7	40.3	214.0	-2	0
	8	70.9	47.9	291.9	-5	0
Seattle Lightfoot^2	6	55.8	37.2	308.4	-1	0
	8	57.2	58.7	323.0	-2	-5
Sure-Flex	2	45.9	36.9	245.1	-2	-5
	4	39.6	28.4	218.4	-5	5
	6	49.4	32.3	257.2	-2	5
Trias$^+$	2	61.8	36.7	410.3	-5	0
	3	72.1	33.8	381.5	-5	0
TruStep	Compliant	75.2	39.1	190.4	-5	0
	Moderate	88.8	31.4	245.5	-5	5
	Stiff	106.9	32.8	292.6	-2	0

Table A2. Heel (-15° sagittal; 0° coronal), forefoot (either 30° sagittal or the greatest orientation without slippage; 0° coronal) and maximum energy storage values for all feet. The orientation of the maximum energy stored is also reported.

Feet		Heel Energy Stored (N*mm)	Forefoot Energy Stored (N*mm)	Maximum Energy Stored (N*mm)	Maximum Energy Storage Location	
Foot Style	**Stiffness Category**				**Sagittal (°)**	**Coronal (°)**
Seattle Catalyst 9	4	1590	9385	9982	15	10
	6	1196	10646	13334	25	10
Vari-Flex w/EVO	4	2591	15682	15792	30	10
	5	2144	7092	8410	15	10
	6	1245	13862	15060	25	10
	Small Wedge	1409	13690	15111	25	10
	Medium Wedge	1473	13871	15560	25	10
	Large Wedge	1969	13844	15248	25	10
	7	1839	6326	7764	15	10
	8	1683	11576	13539	25	10
	9	1547	2878	4156	10	10
Sierra	4	2939	11502	13483	25	-10
	6	2286	9217	11005	25	10
	Medium Wedge	2565	9412	11300	25	10
	8	2063	6931	9427	25	10
Seattle Lightfoot^2	6	2227	11055	13338	25	10
	8	2147	9421	10251	25	10
Sure-Flex	2	2862	15823	17665	25	-10
	4	2702	13220	16183	25	-5
	6	2338	11991	14477	25	-10
Trias$^+$	2	1562	12258	13559	25	-10
	3	1344	11160	12722	25	-10
TruStep	Compliant	1502	14950	18533	25	-10
	Moderate	1228	15150	19026	25	-10
	Stiff	1182	12164	16577	25	10

Table A3. Linear correlation between mean recommended weight and stiffness. The slope of the fit (β) and the coefficient of determination (r^2) are reported.

	Orientation (°)	**-15**	**-10**	**-7.5**	**-5**	**-2**	**-1**	**0**	**1**	**2**	**5**	**10**	**15**	**20**	**25**	**30**
Vari-Flex w/ EVO	**β (N/mm per kg)**	0.47	0.39	-1.10	-0.07	2.11	2.24	1.65	1.23	1.07	-0.37	0.39	0.25	-0.05	-0.23	0.03
	r^2	0.99	0.82	0.81	0.02	0.98	0.98	0.92	0.96	0.92	0.62	0.96	0.94	0.84	0.63	0.39
Sierra	**β (N/mm per kg)**	0.40	0.00	-0.60	1.86	1.56	1.34	1.00	0.65	0.60	0.14	0.62	0.16	0.14	0.14	0.20
	r^2	1.00	0.00	0.46	1.00	1.00	0.99	1.00	0.99	1.00	0.12	1.00	0.52	0.69	0.73	0.99
Sure-Flex	**β (N/mm per kg)**	0.07	-0.36	-0.27	0.01	0.39	0.73	0.57	0.42	0.09	-0.38	-0.04	0.48	0.34	0.14	-0.06
	r^2	0.19	0.39	0.26	0.00	0.04	0.19	0.22	0.06	0.00	0.31	0.01	0.97	0.99	0.93	0.21
TruStep	**β (N/mm per kg)**	0.46	0.92	1.05	-0.14	1.84	1.77	1.33	0.82	0.49	-0.09	-1.64	-0.43	-0.16	-0.09	-0.08
	r^2	1.00	0.96	0.99	0.05	0.98	0.99	0.99	0.89	1.00	1.00	1.00	0.62	0.70	0.44	0.47

Table A4. Linear correlation between mean recommended weight and energy stored. The slope of the fit (β) and the coefficient of determination (r^2) are reported.

	Orientation (°)	**-15**	**-10**	**-7.5**	**-5**	**-2**	**-1**	**0**	**1**	**2**	**5**	**10**	**15**	**20**	**25**	**30**
Vari-Flex w/ EVO	**β (N*mm per kg)**	-14.09	-27.58	-12.90	-3.01	-7.67	-7.85	-6.13	-5.36	-4.21	-5.58	-21.24	-12.57	-8.98	-28.67	-81.01
	r^2	0.89	0.98	0.97	0.63	0.79	0.88	0.87	0.90	0.95	0.83	0.97	0.59	0.27	0.68	1.00
Sierra	**β (N*mm per kg)**	-13.03	-21.75	-1.12	-9.31	-15.11	-13.79	-12.61	-11.32	-10.50	-17.92	-19.48	-20.61	-36.65	-54.01	-67.52
	r^2	0.99	0.99	0.31	0.95	0.98	0.99	0.98	0.99	0.98	0.98	0.82	0.66	0.82	0.90	0.98
Sure-Flex	**β (N*mm per kg)**	-8.15	0.90	2.97	5.76	-4.58	-5.64	-5.89	-6.21	-5.83	-4.40	-29.83	-42.34	-49.23	-43.89	-57.30
	r^2	0.98	0.03	0.23	0.82	0.42	0.76	0.69	0.97	0.86	0.46	0.95	0.84	0.90	0.94	0.92
TruStep	**β (N*mm per kg)**	-4.41	-16.42	-20.41	-9.09	-6.12	-8.55	-11.77	-10.47	-8.38	4.46	22.64	-32.37	-30.45	-40.95	-43.37
	r^2	0.76	0.86	0.93	1.00	0.50	0.72	0.85	0.98	0.98	0.31	0.46	0.68	0.64	0.77	0.80

Table A5. Manufacturer recommended weight ranges at a medium or moderate impact level for each foot tested.

Feet		Recommended Weights (kgs)	
Foot Style	**Stiffness Category**	**Minimum**	**Maximum**
Seattle Catalyst 9	4	70	80
	6	90	100
Vari-Flex w/EVO	4	68	77
	5	78	88
	6	88	100
	Small Wedge	-	-
	Medium Wedge	-	-
	Large Wedge	-	-
	7	101	116
	8	117	130
	9	131	147
Sierra	4	68	77
	6	89	100
	Medium Wedge	-	-
	8	130	147
Seattle Lightfoot[2]	6	46	68
	8	91	113
Sure-Flex	2	54	65
	4	79	95
	6	113	136
Trias[+]	2	80	95
	3	95	110
TruStep	Compliant	59	68
	Moderate	86	95
	Stiff	127	136

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