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Amputee Locomotion: Determining the Inertial Properties of Running-Specific Prostheses

BS Baum, MP Schultz, A Tian, B Shefter, EJ Wolf, HJ Kwon, and JK. Shim

Department of Kinesiology, University of Maryland, College Park, MD

Abstract

Objectives—To (1) test the validity of a trifilar pendulum in estimating moments of inertia (MOI) for running-specific prostheses (RSPs), (2) provide RSP inertial property values for the scientific community, and (3) develop a predictive equation to estimate RSP center of mass (CM) positions.

Design—An aluminum block with known MOI was used for verifying the accuracy of the trifilar pendulum MOI measurements. MOI errors were investigated by systematically misaligning the block and pendulum principal axes across a range of 1–10 cm. Mass, CM position, and MOI were tested across four RSP designs having three stiffness categories each.

Setting—University biomechanics laboratory.

Specimens—Freedom Innovations Nitro, Ossur Cheetah, Ossur Flex-Run, Otto Bock 1E90. Three stiffness categories per RSP were examined.

Interventions—Not applicable.

Main Outcome Measures—MOI errors from known values and principal axis misalignments between RSPs and pendulum; mass, CM positions, RSP principal axis MOIs; predictive equation CM position errors.

Results—The trifilar pendulum estimated MOI within $-6.21 \times 10^{-5} \text{ kg}\cdot\text{m}^2$ (1% error) for a block with known MOI. Misalignments of 1cm - 5cm between the RSPs' and pendulum's CM yielded errors from 0.00002 to 0.00113 $\text{kg}\cdot\text{m}^2$ (0.3 – 59.2%). Each RSP's inertial properties are presented. MOI about any axis varied 0.0038 $\text{kg}\cdot\text{m}^2$ across stiffness categories; MOI differed up to 0.0132 $\text{kg}\cdot\text{m}^2$ between different designs. The predictive CM equation erred between 0.010–0.028 m when using average input values across an RSP design.

Conclusions—Trifilar pendulums can accurately measure RSP MOI. RSP inertial properties differed slightly across stiffness categories within each design, but differed more substantially across different RSP designs. Using a predictive equation to estimate RSP CM positions can provide adequate data, but directly measuring CM positions is preferable.

Keywords

mass; center of mass; moment of inertia; prosthesis; amputation

Introduction

Intact limb inertial properties [mass, center of mass (CM) position, and moments of inertia (MOI)] and regression equations have been established through cadaveric studies¹⁻³ and body scanning methods⁴⁻⁶. In individuals with lower extremity amputation, prosthetic components replace lost limbs, and the inertial properties of the resultant limb-prosthesis are altered. Researchers routinely approximate the inertial properties of walking prostheses by using intact limb values even though the inertial properties may differ^{7, 8}. Some researchers suggest that modeling prosthetic feet using the same marker placements and inertial properties as intact limbs produces reasonably acceptable error levels in gait parameters during stance phase⁹⁻¹¹. However, other research supports the notion that prosthetic foot inertial properties significantly impact the resultant joint kinematic and kinetic estimations during both stance and swing phases^{7, 12-14}. In this case, more accurate estimations of prosthesis inertial properties are required. With the advent of running-specific prostheses (RSPs), these prosthetic components no longer resemble the intact foot and ankle complex, and they have much smaller masses than the anatomical parts they replace. It is therefore reasonable to assume that RSPs also have substantially different CM positions and MOIs than intact limbs. RSPs are prescribed in different stiffness categories according to the patient's weight and activity level. Manufacturers can alter RSP stiffness by layering more or less carbon fiber in the keel, which would alter the inertial properties of RSPs. However, the extent of these effects has not been reported in the literature. Currently there is very limited information on RSP inertial properties, measurements of these properties, and the effects that these properties have on joint biomechanics. While RSP mass is simple to measure using a scale, the CM position and MOIs require additional equipment and can be more difficult to determine. To our knowledge, only one study to date¹⁵ has reported any inertial property values for RSPs. In that study, the inertial properties for one double amputee subject's running prostheses (Ossur Cheetah) were determined from a "pendulum device," but the method itself was not described.

Moments of inertia may be measured using a variety of acceleratory and oscillatory methods¹⁶. Acceleratory methods rely on non-periodic motion such as a falling weight or rolling on a ramp and are affected by the presence of damping. Oscillatory methods rely on periodic motion, and include different pendulum types, such as physical, torsional, and multifilar. Physical pendulums suspend objects using rigid attachments that swing about a pivot point while torsional pendulums are usually disks containing torsional springs that twist about their vertical axis. Multifilar pendulums suspend objects by multiple wires and also rotate about their vertical axes, but the restoring rotational force is supplied by the gravitational field rather than elasticity of the suspension as in torsional pendulums.

Physical pendulums are most commonly used in the prosthetic literature to measure prosthesis MOIs, although detailed descriptions of pendulum methodologies are usually lacking. Additionally, the choice of using a physical pendulum over other types of pendulums for measuring prosthesis MOIs has not been justified to our knowledge. Torsional and multifilar pendulums are more accurate (capable of errors less than 1%) than physical pendulums¹⁶, and multifilar pendulums are relatively simple to construct, only requiring a supporting frame, wire, and a lightweight, rigid platform. Physical pendulums generally rely on a joint or bearing that is assumed to be frictionless to make accurate MOI measurements^{17, 18}. In practice, however, bearing friction does exist and, along with air resistance, will slow the period of oscillation and impart error in the inertial estimations. Physical pendulums can significantly degrade the period of oscillation within the first 10 periods¹⁹, affecting lighter objects more than heavier objects. Since RSPs tend to be much lighter than walking prostheses, physical pendulums will impart larger errors in MOI estimations for RSPs than they will for walking prostheses. One solution to this problem is

to perform multiple oscillation trials with the pendulum and use only the first period under the assumption that it best represents the true period of oscillation^{17, 19}. An alternative solution is to use other pendulum designs that do not rely on bearings, such as multifilar pendulums (referring to the number of wires suspending the object). These pendulums do not use bearings thus minimizing issues caused by friction and allow measurements of more periods of oscillation. A trifilar pendulum suspends a frame or platform from three equidistant wires about which rotation occurs. While trifilar pendulums are accurate, it is often impossible to ensure exact alignment of the CMs and axes of interest in the system, especially with non-uniformly shaped objects such as RSPs. The effects of these misalignments on RSP MOI measurements are currently unknown and will be investigated as part of pendulum validity testing.

This study was designed to (1) test the validity of a trifilar pendulum method in estimating the inertial properties for four common RSP designs, (2) measure inertial properties (mass, CM position, and MOIs) for four RSPs, (3) verify the influence of the stiffness on the inertial properties for RSPs, and (4) develop a predictive equation to estimate RSP CM positions. It was hypothesized that (1) the trifilar pendulum method would accurately measure MOI to within 1% error and (2) that RSPs with higher stiffness categories would have larger masses and MOIs.

Methods

Experiments were designed to test the validity of the trifilar pendulum, measure inertial properties of RSPs, verify the influence of the stiffness on the inertial properties for RSPs, and develop a predictive equation to estimate RSP CM positions. The inertial properties of RSPs were measured using a scale, reaction board, and trifilar pendulum for mass, CM position, and MOI, respectively. Four commonly available RSPs were evaluated including the Freedom Innovations^a Nitro, Ossur^b Cheetah, Ossur^b Flex-Run, and Otto Bock^c 1E90. Inertial properties from three different stiffness categories were measured from each prosthesis model to identify whether stiffness influenced inertial properties within each model type. Stiffness categories are typically prescribed according to user body mass and activity level. Higher category numbers represent increased stiffness and correspond to greater weight and activity intensity. Stiffness categories are not standardized across manufacturers, so a comparable range of categories for each prosthesis was tested, reflecting a common range of population masses (Table 1).

Trifilar Pendulum Validation

A trifilar pendulum was constructed to measure objects' MOIs (Figure 1a–b). An aluminum frame suspended the trifilar pendulum (Figure 1a), which comprised a plexiglass equilateral triangle suspended from its corners by equidistant wires (Figure 1b). A laser sensor (model BJN50-NDT, Autonics^d) measured the pendulum's period of oscillation. The sensor was aligned such that the laser would be interrupted when a corner of the trifilar plate passed the sensor. Two consecutive passes determined one full period of oscillation. To validate the system set-up, a rectangular aluminum block with known mass (2.450 kg) and MOI about its horizontal (0.0061 kg·m²) and vertical (0.0023 kg·m²) axes was tested using the same protocol used for the RSPs. Data were collected, and MOIs were calculated and compared to the object's known MOIs. Estimation error was defined as the difference between the measured and known inertial value about that axis.

^aFreedom Innovations, 30 Fairbanks, Suite 114, Irvine, CA 92618

^bOssur, Grjóthals 5 110 Reykjavik, Iceland

^cOtto BockHealthCare GmbH, Max-Näder-Straße 15, D-37115 Duderstadt, Germany

^dAutonics USA, Inc., 1353 Armour Blvd., Mundelein, IL 60060

Inertial Property Measurements: Mass and Center of Mass Position

Prosthesis masses were measured using a standard scale with a resolution of 0.001 kg (Digital Food Scale, The Sharper Image^c). Each RSP's CM position in the sagittal plane (x-y plane) was measured using a reaction board method^{20–23} and the principal axes were defined to originate at the CM (Figure 2). Each prosthesis design contained a linear “arm” section at its proximal end that was used as a reference to define the principal axes. For the Nitro and Flex-Run models, the most proximal linear segment was used to define the x-axis (antero-posterior). For the Cheetah and 1E90 models, the proximal end was used to define the y-axis (superior-inferior). In all prostheses, the z-axis was parallel to the width of the prosthesis, and orthogonal to the previously defined axis. The final principal axis was defined as orthogonal to both existing axes. The trifilar pendulum's platform CM was determined as the centroid of the triangle with its principal axis orthogonal to the ground.

Inertial Property Measurements: Moment of Inertia

The MOI about the principal axes of each prosthesis was estimated by placing the prosthesis on the trifilar pendulum and measuring the periods of oscillation, as described by du Bois et al²⁴. Prostheses were placed on the pendulum platform by aligning the platform's CM with the RSP's CM. Additionally, the RSP's principal axis of interest was aligned with the pendulum platform's axis of rotation (Figure 3). The platform-prosthesis system was then oscillated about the primary axis of rotation. Two trials of 25 oscillations were collected for each principal axis, and the resultant periods of oscillation were averaged for estimation of MOI. The period of oscillation, τ , was measured and the MOI about each principal axis originating at the CM was calculated via Equation 1²⁴.

$$I_{yy} = \frac{R^2 m g \tau^2}{4\pi^2 L} \quad [1]$$

where I_{yy} is the MOI about the pendulum's oscillating axis, R is the distance from each wire connection to the center of axis of rotation, m is the object mass object, g is acceleration due to gravity, L is the wire length, and τ is the period of oscillation. When adding an object of unknown inertia, the mass and inertia from Equation 1 can be split into components of the frame and object:

$$m = m_P + m_{RSP} \quad [2]$$

$$I_{yy} = I_{Pyy} + I_{RSPyy} \quad [3]$$

where subscripts P and RSP represent the platform and RSP, respectively. Therefore, MOI of the RSP can be calculated using Equation 4²⁴:

$$I_{RSPyy} = \frac{R^2 g \tau^2}{4\pi^2 L} (m_P + m_{RSP}) - I_{Pyy} \quad [4]$$

In trifilar pendulums, it is often impossible to ensure exact alignment of the centers of mass and axes of interest of the system, especially when using non-uniformly shaped objects such as prostheses. Mathematically, MOI error, Δ , due to translational misalignment can be expressed by²⁴

^cThe Sharper Image, 1450 Broadway, 3rd Floor, New York, NY 10018

$$\varepsilon_D = -\frac{m_{RSP} D^2}{m_P + m_{RSP}} \left(m_P + \frac{m_{RSP} g \tau^2}{4\pi^2 L} \right) \quad [5]$$

where m_{RSP} is the RSP mass, m_P is the pendulum platform's mass, D is the misalignment distance between the platform and RSP CMs, g is acceleration due to gravity, τ is the period of oscillation, and L is the wire lengths suspending the platform. D is influenced by the increased inertia of the system (first term) and the change in weight distribution and center of rotation due to the new resultant CM position (second term, in parentheses) caused by the misalignment of the platform and RSP's centers of mass. Errors in MOI due to translational misalignment were estimated for each RSP using Equation 5.

Rotational misalignment can also affect the accuracy of inertial calculations when oscillating the prosthesis about its principal axes. Each RSP's curved design prevented it from naturally balancing with its principal axes aligned with the platform's axis of rotation. Double-sided tape and light-weight foam were used to secure the prostheses. Levels and drop-lines were aligned with marked principal axes to ensure the desired alignment. To test the effects of rotational misalignment, the middle category of each RSP type was re-tested with its x- and y-axes tilted $+5^\circ$ (Figure 4a) and -5° (Figure 4b). MOI was calculated following the same protocol and compared to the MOI of the prosthesis with its principal axes aligned to vertical.

Development of CM Predictive Equation

An equation was developed to estimate the CM position for each RSP model relative to the most proximal ("head") and most distal ("toe") point on the prosthesis. Both of these markers were positioned on the midlines of the RSPs. The equation can be used to estimate the CM of a prosthesis in the absence of a reaction board or other equipment needed to directly measure a prosthesis' CM. The CM position of any RSP relates to the head and toe via Equation 6:

$$\vec{P}_{CM} = r[R]\vec{P}_T \quad [6]$$

where $\vec{P}_{CM}$ is the head-CM position vector, $\vec{P}_T$ is the head-toe vector, r is the ratio of $|\vec{P}_{CM}|$ to $|\vec{P}_T|$, and $[R]$ is the rotation matrix with angle between $\vec{P}_{CM}$ and $\vec{P}_T$. Figure 5 shows a schematic of the relationship between the CM, head, and toe of an RSP with respect to Equation 6. The average r values and angles between these vectors for all categories of a prosthesis were used to predict the CM position for each prosthesis.

Results

System validation with the aluminum block with known MOI showed that the trifilar pendulum was accurate. The error in MOI was $-6.21 \times 10^{-5} \text{ kg}\cdot\text{m}^2$ for the horizontal and $-2.65 \times 10^{-6} \text{ kg}\cdot\text{m}^2$ for the vertical position of the aluminum block, which represent a 1% and 0.1% error in the results respectively. The period of oscillation had minimal degradation across 25 consecutive oscillations (Figure 6).

Mass and CM position varied across each RSP design (Tables 2 and 3, respectively). For all prosthesis designs, the z-axis MOI corresponding to the anatomical flexion/extension axis resulted in the largest MOI whereas the y-axis (anatomical internal/external rotation) had the smallest MOI (Table 2). RSPs resembling a "C" shape, e.g. the Freedom Innovations^a Nitro

and Ossur^b Flex Run, had the lowest mass and MOI, while RSPs resembling a “J” shape, e.g. the Ossur^b Cheetah and Otto Bock^c 1E90, had greater masses and MOI values.

Errors in MOI increased due to greater translational misalignment between the RSP CM and the pendulum platform CM (Figure 7). The Nitro Category 3 y-axis had the lowest mass and CM of any tested prosthesis and axis. Misalignment between the CM of this RSP and the platform's CM of 1cm yielded 0.00002 kg·m² (2.4%) error from MOI measured with CMs aligned. The 5cm misalignment yielded 0.00038 kg·m² (59.2%) error and 10cm misalignment yielded 0.00236 kg·m² (237.0%) error. The 1E90 Category 2351b z-axis had the greatest mass and CM of any tested prosthesis and axis. Misalignments of 1cm, 5cm, and 10cm resulted in errors of 0.00005 kg·m² (0.3%), 0.00113 kg·m² (6.7%), and 0.00451 kg·m² (26.8%), respectively. As the mass and MOI of the RSP increased, the magnitude of the errors induced by misalignment increased. However, the error as a percent of the expected MOI was inflated more in RSPs with lower mass and MOI. For each RSP, rotationally misaligning the y-axis resulted in a greater percentage error than misaligning the x-axis since the y-axis had a lower MOI (Table 4).

As RSP stiffness categories increased, the mass and MOI about each principal axis also increased for each RSP design (Table 2). RSP stiffness did not appear to affect CM position in a consistent way across RSP design (Table 3).

Discussion

A trifilar pendulum's ability to measure MOI was validated against a block with known MOI. Mass, CM positions, and MOIs were estimated for four RSP designs with three stiffness categories each. Variations in each of these parameters were identified in each different type of prosthesis design across stiffness categories. The hypothesis that the trifilar pendulum method would accurately measure MOI to within 1% error was supported. The hypothesis that RSPs with higher stiffness categories would have greater masses and MOIs was also supported.

The high accuracy (± 1% error) and minimal degradation in the period of oscillation measurement across multiple oscillations support using the trifilar pendulum method for estimating prosthesis MOIs. Trifilar pendulums measure more accurate periods of oscillation and MOI estimations than physical pendulums¹⁶ commonly used in prosthetic studies^{15, 17}. In part this is due to the ability of trifilar pendulums to generate consistent periods of oscillation across multiple consecutive measurements while physical pendulums typically rely on bearings that impart friction that quickly degrades the period of oscillation^{17, 19}.

One criticism of the trifilar pendulum method is that it can induce MOI estimation errors if the pendulum platform's CM and the RSP's CM are not properly aligned²⁴. Translational misalignments cause a shift in the system's CM and the pendulum no longer oscillates about the intended axis of rotation. Rotational misalignments estimate the MOI about an axis different than the axis of interest. The errors reported herein correspond well when compared to errors reported for intact limb inertial estimations that can vary substantially depending on the method used to measure these parameters. Rao et al. (2006) identified significant differences between six methodologies (one geometric model, two cadaveric-based models, and three mass scanning models) for estimating inertial properties of the intact foot, shank, and thigh segments²⁵. Estimated MOIs for intact limbs are reported to differ by between 0.0025–0.0031 kg·m² for the foot, depending on the calculation method^{26, 27}. In the current study, it took an 8cm misalignment between the platform CM and CM of the RSP with the greatest MOI to induce an error within this range (Figure 7). Misalignments ≤ 5cm for any RSP resulted in errors less than 0.0012 kg·m², 50% lower than

differences in intact foot MOIs due to measurement technique differences. This indicates that using a trifilar pendulum to estimate MOIs of prosthetic components will yield errors less than those currently accepted in the literature for intact limbs, as long as the CM of the prosthetic device is aligned within 8cm of the pendulum's CM.

Each prosthesis' CM position was calculated using a reaction board, and a predictive equation was developed to estimate these positions using the relationship between the most proximal point, most distal point, and the CM position of a particular prosthetic design. The equation exactly predicted the CM when the category-specific inputs (vector ratios and angles) were used. When using the average ratio and angle for each prosthesis, a majority of the CMs were predicted to within less than one centimeter of error along the x- and y-axes. Several predictions, however, resulted in errors greater than 1 cm with a maximum error of 2.8 cm. The larger errors were a result of a greater range of ratio and angle values across stiffness categories of a particular prosthetic design. Using different body segment parameter models (e.g. cadaveric vs. body scanning-based regression equations) to predict the intact foot CM position are shown to vary by greater than 2 cm in the predicted positions²⁵. This suggests that CM predictions in this study are reasonable; however, directly measuring prostheses' CM positions is recommended when possible to ensure the most accurate data for joint kinetic estimations from inverse dynamics equations.

Limitations

CM and MOI measurements are limited to the prostheses in their uncompressed form (with no load as in running swing phase). Inertial parameters will change when the prosthesis is compressed, e.g. during running stance phase. However, since the loads required to compress the prosthesis are very large relative to the changes in inertial properties during loading, it is likely that these inertial changes would negligibly affect the resultant inverse dynamics estimations of joint kinetic values. Rather the external loads (i.e. ground reaction forces) would dominate the inverse dynamics predictions. Additional studies are needed to determine these effects and to discriminate between the effects of inertial changes and the loads required to produce those changes.

Another limitation is that the accuracy of the trifilar pendulum was only tested against one known object (two known MOIs). The MOIs about the horizontal and vertical axes of the aluminum block approximated many of the RSP MOIs; however, several MOIs measured in this study nearly doubled the largest MOI of the aluminum block. System error could vary depending on the object's inertial property features. Our results obtained similar errors to those reported previously for trifilar pendulums (~1%)¹⁶, so it is likely that system accuracy will remain relatively consistent for a variety of objects. For reliable results, the MOI of the test object and pendulum platform must be significantly greater than the MOI of the platform alone¹⁶. Therefore, trifilar pendulum accuracy should always be checked against objects with very small MOIs, but the system will remain accurate for objects with MOIs significantly larger than the pendulum platform.

The trifilar pendulum method also does not account for the effect of air resistance. However, this effect is most likely negligible with the low accelerations during oscillation, so MOI results are not anticipated to change. Additionally, this study only included inertial property estimations for RSP keels. Socket inertial properties were not investigated nor were any pylons or connecting hardware. The mass and MOI for sockets may not be trivial and could affect kinetic estimations during running. The methods described in this study can be used to measure inertial properties of sockets and pylons/hardware either separately or as a combined unit along with an RSP. Predictive equations for socket CM and MOI would be a valuable addition to the literature in the future, although since sockets are subject-specific, large variability in inertial properties between subjects should be anticipated.

Conclusions

The inertial properties of four commonly prescribed RSPs were measured using a scale, reaction board, and trifilar pendulum. The trifilar pendulum demonstrated accuracy 99% with low period of oscillation degradation across consecutive oscillations. Mass, CM position, and MOI were shown to vary slightly between stiffness categories within a prosthetic design, and they varied more substantially between different prosthetic designs. A predictive equation was presented to estimate the CM position of a prosthesis when direct measurements are not possible. The predictive equation and trifilar pendulum measured inertial properties with errors equal to or less than those found in commonly used predictive methods for intact limb inertial properties. This suggests the presented methods and values presented are within or below currently accepted tolerances for inertial property estimations for gait studies.

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Figure 1.

Custom-built trifilar pendulum. (a) A large aluminum frame suspends (b) a triangular platform by three equidistant wires that allow the platform to rotate about the axis perpendicular to the ground. While rotating, the period of oscillation is measured when one corner of the platform passes a laser sensor (not shown).

Figure 2.

Prosthesis coordinate system definitions. The coordinate systems originate at the measured centers of mass for each prosthesis. The z-axis is orthogonal to the sagittal plane, with the positive direction pointing away from the reader. See text for axis definitions. See Table 3 for center of mass position values.

Figure 3.

Experimental setup. The prosthesis' primary axes of rotation are aligned with the trifilar pendulum platform's center of mass and axis of rotation. Alignment with the prosthesis' y-axis is shown here.

Figure 4. Rotational misalignment. Inducing (a) $+5^\circ$ and (b) -5° of rotational misalignment between the pendulum platform's axis of rotation and the prosthesis' principal axis (y-axis shown here).

Figure 5.

Estimating center of mass (CM) position. $\vec{P}_T$ is the Head-Toe vector, $\vec{P}_{CM}$ is the Head-CM vector, and θ is the angle between these vectors. x and y represent the 2D coordinate system, originating at the Head, used for the CM estimation. See Equation 6 in the text for additional details.

Trifilar Pendulum Period of Oscillation Measurement

Figure 6.

Trifilar pendulum period of oscillation variability. Exemplar period of oscillation measurements for a running-specific prosthesis using the trifilar pendulum. The graph shows low cycle-to-cycle variability and minimal degradation of the measured period across 25 consecutive oscillations.

Error in Moment of Inertia due to Misalignment

Figure 7.

Translational misalignment error. Error in moments of inertia (MOI) due to misaligning the centers of mass (CM) of the tested running-specific prostheses (RSPs) and the CM of the pendulum's platform by up to 10cm, calculated by Equation 5. The Freedom Innovations^a Nitro C3y (stiffness category 3, y-principal axis) had the lowest mass and MOI of the tested prostheses. The Otto Bock^c 1E90 C235z (stiffness category 235lb, z-principal axis) had the greatest mass and MOI of the tested prostheses. The shaded area indicates the range of the errors in moment of inertia for all tested prostheses and principal axes due to CM misalignment.

Table 1

Prosthesis Stiffness Categories.

Prosthesis Model	Stiffness Category (body mass range)		
Freedom Innovations Nitro	3 (60–68 kg)	6 (89–100 kg)	7 (101–116 kg)
Ossur Cheetah	3 (60–68 kg)	5 (78–88 kg)	7 (101–116 kg)
Ossur Flex-Run	3 (53–59 kg)	5 (69–77 kg)	7 (89–100 kg)
Otto Bock 1E90	140 lb (63.6 kg)	185 lb (84.1 kg)	235 lb (106.8 kg)

*The body mass range recommended by the manufacturers for each stiffness category is shown in parentheses.

Table 2

Prosthesis Center of Mass (CM) Positions.

Prosthesis Model	Cat	r	Avg r	(rad)	Avg (rad)	Measured CM (m)		Predicted CM (m)		Error (m)	
						x	y	x	y	x	y
Freedom Innovations Nitro	3	0.366		-1.128		-0.053	-0.069	-0.062	-0.054	0.009	-0.015
	6	0.359	0.362	-1.091	-1.185	-0.051	-0.069	-0.063	-0.053	0.012	-0.016
	7	0.362		-1.336		-0.058	-0.063	-0.054	-0.061	-0.004	-0.002
Ossur Cheetah	3	0.504		-0.328		0.025	-0.264	0.018	-0.292	0.007	0.028
	5	0.589	0.556	-0.377	-0.360	0.019	-0.304	0.022	-0.286	-0.003	-0.018
	7	0.574		-0.374		0.021	-0.300	0.024	-0.290	-0.003	-0.010
Ossur Flex-Run	3	0.398		-0.951		-0.065	-0.072	-0.069	-0.070	0.004	-0.002
	5	0.418	0.404	-1.044	-0.999	-0.065	-0.079	-0.059	-0.079	-0.006	0.001
	7	0.395		-1.003		-0.058	-0.078	-0.059	-0.080	0.001	0.003
Otto Bock 1E90	140lb	0.597		-0.441		0.017	-0.307	0.019	-0.286	-0.002	-0.021
	185lb	0.538	0.562	-0.452	-0.429	0.029	-0.278	0.037	-0.287	-0.008	0.009
	235lb	0.537		-0.392		0.032	-0.278	0.023	-0.289	0.009	0.011

Cat = stiffness category

r = ratio of measured prosthesis head-CM to head-toe vector magnitudes

= angle, in radians, between measured head-CM and head-toe vectors

Measured = CM position measured with a reaction board

Predicted = CM position predicted from Equation 6 (see text) using Avg r and Avg

Error = difference between Measured and Predicted CM positions, in m

Table 3

Prosthesis Masses and Moments of Inertia.

Prosthesis Type	Category	Mass (kg)	Moment of Inertia (kgm ²)		
			x - axis	y - axis	z - axis
3	0.307	0.0021	0.0010	0.0029
	6	0.349	0.0024	0.0012	0.0033
	7	0.366	0.0026	0.0012	0.0036
3	0.492	0.0123	0.0021	0.0139
	5	0.511	0.0127	0.0023	0.0143
	7	0.539	0.0136	0.0022	0.0152
3	0.416	0.0037	0.0014	0.0047
	5	0.437	0.0037	0.0017	0.0051
	7	0.466	0.0040	0.0017	0.0054
1401b	0.543	0.0116	0.0027	0.0130
	1851b	0.605	0.0131	0.0035	0.0152
	2351b	0.677	0.0144	0.0042	0.0168

Category = stiffness category

x-axis = anatomical ab/adduction

y-axis = anatomical internal/external rotation

z-axis = anatomical flexion/extension

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Table 4

Rotational Misalignment Error.

Prosthesis Model	x-axis Error			y-axis Error		
	-5°		+5°	-5°		+5°
	kg·m ²	%	kg·m ²	kg·m ²	%	kg·m ²
Freedom Innovations Nitro	0.00065	27.1	0.00071	29.6	0.00086	71.7
Ossur Cheetah	-0.00030	2.4	0.00077	6.1	0.00046	20.0
Ossur Flex-Run	-0.00001	0.3	0.00012	3.2	0.00018	10.6
Otto Bock 1E90	0.00030	2.3	0.00165	12.6	0.00076	21.7
						0.00075
						21.4

* Values represent the raw (kg·m²) and percent (%) difference in moment of inertia measured when the prosthesis' principal axis is properly aligned in the trifilar pendulum and when misaligned by ±5° . Exemplar data include the middle stiffness category for each prosthesis.

-5° = principal axis of prosthesis rotated in -5° misalignment

+5° = principal axis of prosthesis rotated in +5° misalignment