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Short communication

Cross-validation of a portable, six-degree-of-freedom load cell for use in lower-limb prosthetics research

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ABSTRACT

The iPecs™ load cell is a lightweight, six-degree-of-freedom force transducer designed to fit easily into an endoskeletal prosthesis via a universal mounting interface. Unlike earlier tethered systems, it is capable of wireless data transmission and on-board memory storage, which facilitate its use in both clinical and real-world settings. To date, however, the validity of the iPecs™ load cell has not been rigorously established, particularly for loading conditions that represent typical prosthesis use. The aim of this study was to assess the accuracy of an iPecs™ load cell during in situ human subject testing by cross-validating its force and moment measurements with those of a typical gait analysis laboratory. Specifically, the gait mechanics of a single person with transtibial amputation were simultaneously measured using an iPecs™ load cell, multiple floor-mounted force platforms, and a three-dimensional motion capture system. Overall, the forces and moments measured by the iPecs™ were highly correlated with those measured by the gait analysis laboratory ($r > 0.86$) and RMSEs were less than 3.4% and 5.2% full scale output across all force and moment channels, respectively. Despite this favorable comparison, however, the results of a sensitivity analysis suggest that care should be taken to accurately identify the axes and instrumentation center of the load cell in situations where iPecs™ data will be interpreted in a coordinate system other than its own (e.g., inverse dynamics analysis).

1. Introduction

Portable load cells have emerged as promising tools in the field of lower-limb prosthetics for their ability to evaluate unconstrained, dynamically-complex tasks (Berme et al., 1976; Boone et al., 2005, 2013; Dumas et al., 2009; Frossard et al., 2003, 2008, 2010a, 2010b, 2010c, 2011a, 2011b, 2013; Hurkmans et al., 2003; Kobayashi et al., 2012, 2013a, 2013b; Lee et al., 2007, 2008; Neumann et al., 2012, 2013; Nietert et al., 1998; Oehler et al., 2007; Sanders et al., 1997; Schwarze et al., 2013). Perhaps the most versatile of these systems is the recently developed iPecs™ load cell (Intelligent Prosthetic Endo Component System; College Park Industries, Inc., Fraser, MI), a wireless, six-degree-of-freedom force transducer designed to fit easily into an endoskeletal prosthesis via a universal mounting interface. While preliminary tests performed by the manufacturer have verified the accuracy of the iPecs™ during static loading conditions, the validity of this system has not been evaluated for activities that represent more typical prosthesis use. The primary aim of this study was to assess the accuracy of an iPecs™ load cell during in situ human subject testing by cross-validating its measurements with those of a gait analysis laboratory. Accordingly, this study is the first to provide insight into the validity of the iPecs™ load cell as a tool to enhance the biomechanical assessment of persons with lower-limb loss.

2. Methods

See Appendix A for a detailed description of the methodology.

2.1. Subject

All experimental procedures were approved by Northwestern University's Institutional Review Board. Data were collected on one male subject (age: 67 yr, height: 1.87 m, mass: 89.5 kg) with unilateral, transtibial amputation (etiology: right-side trauma). Prior to data collection, the subject provided his informed, written consent. The subject was community ambulatory (MFCL K3) and was an experienced prosthesis user; he was able to walk continuously and unaided across an 8-m walkway and was able to voluntarily adjust his walking speed.

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2.2. Data collection

The subject wore his existing patellar tendon bearing socket with supracondylar suspension, a rigid pylon, an Otto Bock 1D10 (R27) prosthetic foot, and an athletic shoe. The iPecs™ was mounted between the subject's prosthetic socket and rigid pylon using a four-hole pyramid adapter designed to isolate residual strain caused by set screw tightening (Appendix A, Fig. A1). All components in the prosthesis were aligned by a certified prosthetist.

Quantitative gait data were collected in the Jesse Brown VA Medical Center Motion Analysis Research Laboratory. Markers were placed on the subject to allow for a standard gait analysis and the iPecs™ was zeroed (Appendix A). The subject was instructed to walk at a freely-selected, normal speed across an 8-m, level walkway until at least five clean foot strikes were obtained on each of four force platforms. A clean foot strike was defined as a step in which the subject's foot was entirely and exclusively confined to the perimeter of the force platform. Four force platforms were used in this study to reduce measurement bias. To investigate a range of loading conditions, the procedure was repeated at multiple walking speeds.

2.3. Data analysis

A quasi-static analysis (Appendix A) was used to compare the forces and moments measured by the iPecs™ ($\vec{F}_{\text{iPecs}}^{\text{iPecs}};\vec{M}_{\text{iPecs}}^{\text{iPecs}}$) to those measured by the gait analysis laboratory ($\vec{F}_{\text{GRF}}^{\text{iPecs}};\vec{M}_{\text{GRF}}^{\text{iPecs}}$). Root mean square errors (RMSE) were calculated for all steps across each walking speed (Appendix A). Furthermore, magnitudes of offset between each sample of iPecs™ and transformed force platform data (i.e., all steps across all speeds) were calculated and grouped into five, linearly-spaced bins according to the magnitude of load measured by the gait analysis laboratory. The mean and standard deviation within each bin was then plotted as a function of load measured by the gait analysis laboratory.

To investigate the extent to which a 2 mm error in marker placement may have influenced the coordinate transformation used to cross-validate the two force-measurement systems, a sensitivity analysis was performed in which the marker-based coordinate system of the iPecs™ load cell was randomly and simultaneously perturbed according to a Monte Carlo ($n=1000$) sampling procedure (Appendix A).

2.4. Statistical analysis

To explore the association between forces and moments measured by the iPecs™ and those quantified by the gait analysis laboratory, a linear regression analysis was performed using SPSS 20.0 (SPSS Inc., Chicago, IL). All data points collected during the stance phase of the subject's freely-selected walking speed were considered in this linear regression analysis. Data points with a z-score greater than 3.29 were identified as outliers and discarded (Field, 2000). Pearson correlation coefficients, r, were calculated to quantify the strength of the association.

3. Results

In total, data were collected for 47 steps distributed across three walking speeds: slow: 1.0 ± 0.03 m/s, freely-selected: 1.1 ± 0.04 m/s, and fast: 1.4 ± 0.04 m/s (Table 1).

Table 1
Number of steps collected per force platform.

Force platform:	Slow	Freely-selected	Fast	Total
FP 1	3	5	3	11
FP 2	3	5	3	11
FP 3	3	6	3	12
FP 4	3	8	2	13
Total	12	24	11	47

3.1. Cross-validation of force and moment data

As shown in Fig. 1, tri-axial forces and moments measured by the iPecs™ ($\vec{F}_{\text{iPecs}}^{\text{iPecs}};\vec{M}_{\text{iPecs}}^{\text{iPecs}}$) closely approximated those measured by the gait analysis laboratory ($\vec{F}_{\text{GRF}}^{\text{iPecs}};\vec{M}_{\text{GRF}}^{\text{iPecs}}$). A nominal but persistent offset was observed in the medial/lateral force profile as well as in the abduction/adduction moment profile. Offsets were also observed during early stance in the anterior/posterior force and flexion/extension moment profiles. The largest offset in the superior/inferior force profile was observed during late stance (approximately 80%), at which time a large flexion/extension moment was simultaneously observed. Across all speeds, mean RMSEs were less than 3.4% and 5.2% full scale output across all force and moment channels, respectively (Table 2).

Linear regression revealed a significant correlation between the forces and moments measured by the iPecs™ and those measured by the gait analysis laboratory (two-tailed significance, $p<0.05$). Pearson correlation coefficients were 0.98, 0.99, and 0.99 for the medial/lateral, anterior/posterior, and superior/inferior force profiles, and 0.98, 0.86, and 0.87 for the flexion/extension, abduction/adduction, and internal/external moment profiles, respectively (Fig. 2). For each force/moment component, the intercept of the best-fit regression line corresponded to the mean RMSE reported in Table 2. For five of the six force/moment components, the slope of the best-fit regression line differed slightly from 1. This suggests that to some extent, errors between the iPecs™ load cell and the gait analysis laboratory were load dependent.

To explore this dependency, the magnitude of offset between the two systems was analyzed (Fig. 3). While the mean magnitude of offset appeared to increase slightly for larger medial/lateral forces and internal/external moments and decrease slightly for larger flexion/extension and abduction/adduction moments, this trend was minimal and consistent with the linear behavior of foil strain gages (Hsieh et al., 2011).

3.2. Sensitivity analysis

Results from the sensitivity analysis indicate that 2 mm of marker placement error had a noticeable effect on the medial/lateral and anterior/posterior force components, potentially accounting for the small offsets observed in these force profiles (Fig. 4). However, marker placement could not explain the offset observed in the superior/inferior force profile during late stance or for the offset observed in the flexion/extension moment profile during early stance.

4. Discussion

This study evaluated the accuracy of an iPecs™ load cell during in situ human subject testing by cross-validating its measurements with those of a gait analysis laboratory. Our findings indicate that the force and moment measurements of the iPecs™ are similar both in pattern and magnitude to those measured by a gait analysis laboratory. We observed maximum RMSEs in the superior/inferior force profile (3.4% full scale, 42 N) and in the flexion/extension moment profile (5.2% full scale, 7 N m) during the subject's fastest walking speed. These values are comparable to both the full-scale accuracy of the iPecs™ during static validation tests (Appendix A, Table A1) as well as RMSEs reported in previous validation studies (Sanders et al., 1997; Dumas et al., 2009). In addition, linear regression revealed a significant correlation between the forces and moments measured by the iPecs™ and those measured by the gait analysis laboratory. In particular, forces and moments in the sagittal plane, which are of primary interest in gait analysis studies, were highly correlated ($r>0.98$, $p<0.001$).

Compared to previous investigations, this study was unique both in its methods and analysis. Namely, we did not use a standard static loading paradigm to cross-validate the iPecs™ (Sanders et al., 1997). Rather, we utilized a human-subject testing protocol to evaluate the iPecs™ under loading conditions that