Ground Reaction Forces Are More Sensitive Gait Measures Than Temporal Parameters in Rodents Following Rotator Cuff Injury

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Disclosures: Pardes AM (N), Freedman BR (N), Soslowsky LJ (5; Orthofix, DJO)

Introduction

Musculoskeletal conditions affect 1 out of every 7 Americans, costing our society an estimated $254 billion yearly.[1] While tissue level animal studies provide valuable insight into the causes and treatment of musculoskeletal injuries and diseases, interpretation of the clinical and translational importance of such studies can be aided with a quantitative measure of resulting limb/joint function in live animals.[2,3] Several human and animal gait analysis studies have observed decreases in temporal parameters (e.g., stance time—how long the foot remains in contact with the ground in a single step) that seem to correspond with decreases in kinetic gait parameters (e.g., vertical ground reaction force). However, the relationship between temporal properties and ground reaction forces during locomotion has not been investigated.[2,4,5] This information is critical given the relative ease and low cost of measuring temporal parameters compared to the more complicated kinetic parameters. Therefore, the objective of this study was to compare the sensitivity of temporal versus kinetic parameters in response to functional changes using a validated gait and force-plate analysis system in rodent models following rotator cuff injury.[2] We hypothesized that temporal and kinetic parameters would correlate and be equally sensitive measures of rodent gait.

Methods

The data used in this study were obtained from our previous studies using rat rotator cuff injury models.[3,6,7] In one study, 28 animals underwent unilateral detachment of the supraspinatus only (SO) or supraspinatus and infraspinatus (SI) rotator cuff tendons and ambulatory measurements were collected preoperatively and at 3, 7, 14, 28, 42, and 56 days post-operatively. To create a more comprehensive and general model, data from the SO and SI groups were combined and used for the correlation and regression analysis in the current study as these groups demonstrated significant differences in shoulder function measured by kinetic gait parameters, as well as tendon and cartilage mechanical and histological properties.[3] Data from two other studies were used to assess the efficacy of the regression model created from the SO and SI data. In one study, 18 animals underwent unilateral detachment of the supraspinatus, infraspinatus, and biceps (SIB) tendons and ambulatory measures were collected identically to the SO and SI groups. In the other study, 20 animals underwent unilateral detachment of the supraspinatus tendon and repair with (RW) or repair without (RWO) post-operative analgesics and ambulatory measurements were collected at 2, 4, 6, 14, and 28 days following surgery. *Correlation analysis:* Pearson's correlation coefficients were calculated between temporal parameters (i.e., braking, propulsion, and stance times) and kinetic parameters (i.e., vertical, braking, and propulsion forces). *Kinetic and temporal parameter sensitivity:* The total number of significant differences in kinetic parameters alone between SO & SI, SIB & baseline, and RW & RWO was compared to the subset of significant differences identified simultaneously in corresponding temporal-kinetic pairs (i.e., vertical force & stance time, braking force & braking time, propulsion force & propulsion time) for each pair of experimental groups. Comparisons between kinetic and temporal parameters were also performed for uninjured and injured (SO and SI, combined) animals at 3, 7, and 14 days. *Regression modeling:* Step-wise backward elimination linear regression analysis was performed on the combined SO/SI data set to select the best temporal variables for predicting kinetic gait parameters. Resulting equations were then used to predict vertical, braking, and propulsion forces for all groups. The total number of known significant differences in experimental ground reaction forces between groups was compared to the number of significant differences identified by predicted kinetic parameters for these groups. *Statistical analysis:* Correlation coefficients and two-tailed p-values were calculated using bivariate Pearson correlation. Comparisons between groups for temporal and kinetic parameters were made using two-tailed t-tests. Significance was set at $p < 0.05$ for all tests (SPSS v20.0).

Results

Correlation analysis: Numerous significant correlations between kinetic, spatial, and temporal parameters were identified (Table 1). As expected, corresponding temporal-kinetic pairs were

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Table 1. Kinetic and Temporal Parameter Correlation Coefficients. Significance key: * ($p < 0.05$), ** ($p < 0.01$), * ($p < 0.001$)**

	Stance Time	Braking Time	Propulsion Time
Vertical Force	0.85***	0.91***	0.53*
Braking Force	0.55*	0.84***	0.84***
Propulsion Force	0.41*	0.77**	0.76**

significantly correlated. *Kinetic and temporal parameter sensitivity*: Known functional differences between groups were successfully identified by temporal parameters at rates of 20%, 29%, and 0% for SO vs. SI, SIB vs. baseline, and RW vs. RWO, respectively (data not shown). Overall, temporal parameters were better able to identify significant functional differences at early time points when the percent difference in kinetic parameters was greatest between experimental groups (Figure 1). *Regression modeling*: Stance and propulsion time were identified as the best variables for predicting vertical, braking, and propulsion force through backward elimination (data not shown). When the regression equations were used to predict ground reaction forces, they successfully predicted 70% of the known significant differences in kinetic parameters between SI and SO (Figure 2). When predicting data sets not used to create the model, the regression equations were less successful at predicting differences in ground reaction forces between groups as expected, especially when these differences were smaller in magnitude. Specifically, the model was able to predict 57% of known significant differences in kinetic parameters between uninjured animals and animals with a three-tendon tear (SIB), whereas it was able to predict 0% of known significant differences in ground reaction forces between animals with or without post-surgical pain relief (RW, RWO).

Discussion

Temporal parameters were consistently less sensitive than ground reaction forces in detecting functional differences in rat gait despite the significant correlations observed between these metrics. While the regression model developed to predict kinetic parameters did aid in identifying significant functional changes compared to temporal parameters alone, only differences that were large in magnitude, such as between injured and uninjured animals, were able to be detected with greater than 50% probability. Therefore, while gait analysis systems without force plates can be efficient and often feature fully automated analyses, they may only be adequate for use when large changes are expected. This agrees with previous rodent studies that found more pronounced differences in ground reaction forces than temporal parameters when evaluating changes in gait.[8,9] Future work may include analyzing other commonly injured joints such as the ankle.

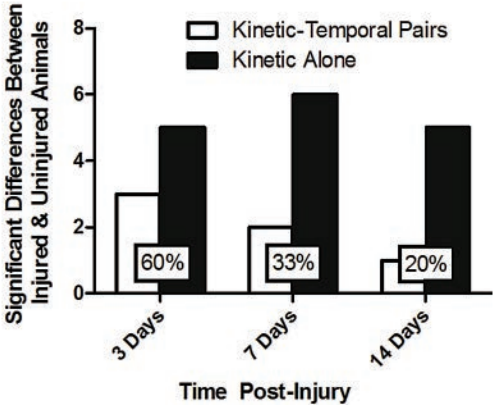

Figure 1. Sensitivity of Kinetic vs. Temporal Gait Parameters. The total number of significant differences observed between injured (SI, SO) and control animals in kinetic parameters (ground reaction forces) (black bars) was compared to the subset of differences identified simultaneously in corresponding kinetic-temporal pairs (e.g., braking force & time) (white bars) at 3, 7, and 14 days post-op

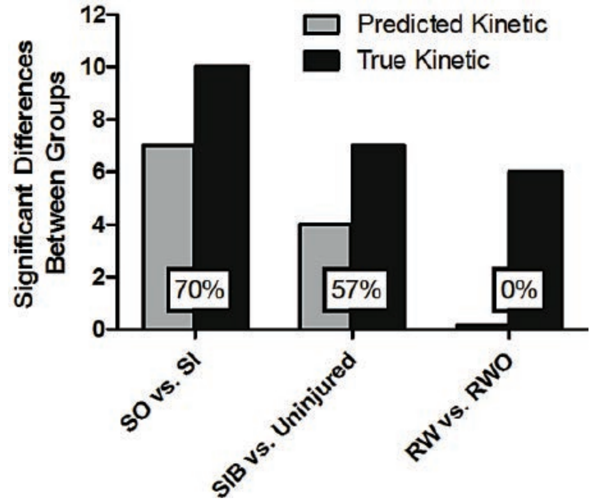

Figure 2. Kinetic Parameter Predictability. Regression modeling was used to predict ground reaction forces from stance & propulsion times for in-model (SI, SO), and out-of-model (SIB, RW, RWO) data sets. Significant differences between groups in predicted kinetic parameters (gray bars) were compared to known significant differences in true kinetic parameters (black bars).

Significance

This study supports the use of ground reaction force quantification as a more sensitive metric of limb/joint function than temporal gait parameters.

Acknowledgements

The authors thank Joseph Sarver, Katie Reuther, Steve Thomas, and Adam Caro for assistance and the NIH/NIAMS for funding.

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