Original Research

# The Validity of a Portable Strain-Gauge Apparatus Versus a Commercial Isokinetic Dynamometer for Evaluating Knee Extension Kinetics

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## Background

Isokinetic dynamometers are widely used when assessing neuromuscular function including knee extension kinetics. However, these dynamometers are often prohibitively expensive and are not portable. Thus strain-gauge technology has grown in popularity.

## Purpose

The purpose of this study was to compare kinetic data captured via an isokinetic dynamometer against an affordable and portable strain-gauge with a treatment plinth during maximal isometric knee extensions.

## Study Design

Cross-sectional study.

## Methods

Healthy participants (8 males and 6 females; age 30.2±7.1 years) volunteered and performed knee extensions at a 90° knee angle on a dynamometer and a treatment plinth with a portable strain-gauge. Peak force (PF), peak rate of force development (PRFD), rate of force development ($RFD_{2080}$) and impulse ($IMP_{2080}$) from 20-80% of onset to peak force were assessed using both strain-gauge and isokinetic dynamometer. Between-device differences were evaluated by the Wilcoxon signed-rank test, Cohen's *d* effect sizes (ES), Pearson's correlation coefficients (*r*), and Bland-Altman plots.

## Results

No significant or meaningful differences were identified between isokinetic and strain-gauge devices (all $p \geq 0.268$, ES≤0.35). However, slightly greater (2.5-9.5%) outputs were observed with the isokinetic dynamometer. Very large significant between-device correlations were found for PF ($r$=0.77, $p$=0.001) and PRFD ($r$=0.73, $p$=0.003), while small and moderate non-significant between-device correlations were found for $RFD_{2080}$ ($r$=0.48, $p$=0.079) and $IMP_{2080}$ ($r$=0.59, $p$=0.060). Bland-Altman plots did not reveal apparent biases from high to low performers.

## Conclusions

These results indicate that the strain-gauge device can produce valid maximal and rapid force expression measurements. Similar results, such as those quantified via an isokinetic device, can be obtained without extreme rigour and constraint. The study's findings

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support using the practically relevant treatment plinth and strain-gauge combination as a suitable alternative to the isokinetic dynamometry for measuring PF and PRFD. Therefore, more rehabilitation and sports performance practitioners can confidently assess knee extension kinetics.

## Level of Evidence

3

## INTRODUCTION

Rate of force development (RFD) and impulse (IMP) are valuable components of force production and neuromuscular capacity.[1-4] These metrics can translate into the ability of motor units to develop force quickly,[1] which can enhance sporting performance,[5,6] and is beneficial in activities that affect the quality of life.[7] Additionally, RFD and IMP may better predict functional abilities than maximal strength or peak force (PF) assessments.[6,8] Rapid force characteristics are also strongly associated with the prevention of falls, the maintenance of balance, stabilizing the body during reactive tasks,[7,9] and providing valuable insight into the stiffness and physiology of the muscle-tendon unit[10] and neural capacity.[1]

A primary consideration of rapid force assessment is related to the availability and practicality of the technology and equipment needed, including back-end analytics. Appreciating the expected variability in RFD and IMP data, a measurement device must contain sensitive, high-frequency components to accurately record this data. Isokinetic testing apparatus, often the standard in open chain joint and muscle-specific force testing,[11,12] collects kinematic and kinetic data in a constrained and standardized manner and hence very little variability is associated with the assessed measures.[11,12] However, research-grade isokinetic dynamometers are prohibitively expensive and non-portable, especially compared to other force assessment tools, such as strain-gauges.

Sports performance and rehabilitation staff often lack affordable, portable, and clinically useful tools to adequately measure and track kinetic force variables from joints such as the knee. While various testing mediums and tools are available, the strain-gauge can offer a lower financial price point, greater portability, and, therefore, higher utility for clinicians to assess neuromuscular function. While shown to be reliable in several contexts,[13,14] limited data exist concerning the validity and transferability of data collected via strain-gauge compared to isokinetic dynamometers. Thus, established practices may be hesitant to transfer their collection protocols from isokinetic dynamometry to portable strain-gauge. Therefore, the purpose of this study was to compare kinetic data captured via an isokinetic dynamometer against an affordable and portable strain-gauge with a treatment plinth during maximal isometric knee extensions. The hypothesis was that there would be no difference in the kinetic data collected by the highly constrained, isokinetic dynamometer device versus those same variables collected on the strain-gauge device.

## METHODS

### STUDY DESIGN

A single-session cross-sectional study design was implemented, comparing various kinetic variables during the knee extensors' maximal voluntary isometric contractions (MVIC) with an isokinetic dynamometer versus strain-gauge device. These two data collection tools were evaluated using three protocols where a range of kinetic variables were assessed. Participants completed three explosive MVICs of the knee extensors for each protocol. Testing was completed bilaterally for all participants. However, only the right leg was used for analysis. Testing order was randomized for each subject, and one rater with ~3 years of experience collected all data.

### PARTICIPANTS

A total of fourteen participants volunteered and completed the study, including eight men and six women. Participants were recruited via posters placed throughout the university campus and by word of mouth; they were predominantly graduate students and university staff. All participants were healthy with no current health conditions limiting strenuous exercise or the ability to complete maximal knee extensions. Participants were excluded if they had a prior surgical intervention that would limit knee extension performance or reported any pain throughout the trials. All participants reported their right leg as dominant (kicking leg). Ethics approval for this study was obtained from the Auckland University of Technology Ethics Committee, and all participants provided written informed consent.

### TESTING EQUIPMENT

The isokinetic device (Humac Norm; CSMi; Lumex, Ronkonkoma, NY) was used as the gold standard for data collection. The isokinetic dynamometer sampling rate was increased to 1000 Hz through custom software (LabView; National Instruments, New Zealand) to match the strain-gauge's sampling frequency and improve the accuracy of RFD and IMP calculations as per previous research.[15,16] The pre-tension threshold for this device was set at 40 Nm (torque), which was reported subjectively as being like the 120 N (force) used with the strain-gauge. The collection threshold for this protocol was 50 Nm.

The strain-gauge device was a wireless force measurement system that consisted of a strain-gauge, Bluetooth connectivity, and an internally designed software package (SPRINZ Laboratories, Auckland University of Technology) sampling at 1000 Hz. The computer, with software visible,


**Figure 1. Experimental set-ups for the isokinetic dynamometer (A), and plinth + strain-gauge (B)**

was placed directly in front of the subject for practice trials, feedback, and the pre-tension threshold. Following pilot testing, the pre-tension mark was set to 120 Newtons (N), while the collection threshold was set to 160 N (i.e., the trial initiation was established once the force produced was above 160 N).[13,14]

PROCEDURE

Two data collection protocols were implemented. Each collection used either the isokinetic dynamometer or the portable strain-gauge with treatment plinth. Kinetic variables were collected at 90º of knee flexion.

*PROTOCOL 1: ISOKINETIC DYNAMOMETER*

Protocol 1 (Figure 1A) had the subject seated upright in the chair of the isokinetic dynamometer at a hip angle of 85º, with shoulder, waist, and thigh constrained by straps to reduce body movement during contractions. This highly restricted method and the isokinetic dynamometer for collecting isometric force was considered the standard for comparison to the strain-gauge.[2,5,15,17] The device was adjusted so the subject's knee joint line was positioned at the center of dynamometer rotation and the ankle fixation pad approximately two centimeters superior to the lateral malleolus. The subject was instructed to place their non-testing limb behind the counterforce pad and use the handles on both sides for each trial.

*PROTOCOL 2: TREATMENT PLINTH WITH STRAIN-GAUGE*

Protocol 2 (Figure 1B) consisted of a clinical plinth (table) and strain-gauge with subject's performing contractions at 90º of knee flexion. This protocol was designed for the implementation of portable strain-gauge technology in a practical setting, such as a physiotherapy clinic. The subject was seated on the edge of a plinth and allowed to self-select a position while meeting the following criteria: 1) the subject must maintain this position throughout the trials; 2) the subject must hold the sides of the table; and 3) the subject must shift towards the side of the table being tested (the line of force must be in line to the fixation point which was located towards the side of the table). Once seated and comfortable, the subject was fixed to the table at 2 cm superior to the lateral malleolus using a low compliance steel chain. A towel was placed under the distal thigh between the thigh and the table to reduce discomfort during expressions of maximal force. The table height was adjusted to maintain a 90º line of force to the fixation angle. Throughout practice trials, the subject was allowed to move and change position. However, no further changes were permitted once the testing began, and the subject's position was recorded for future testing sessions.

The testing angle of the knee joint was confirmed with goniometric measurement to account for tissue and padding deformation. Before any testing trials, the subject completed practice trials which included verbal instructions about the procedure and visual education about the pre-tension position on the computer monitor.

*COLLECTION PROTOCOL*

Participants warmed up by cycling at moderate resistance using a self-selected pace for five minutes. Familiarization using the plinth + strain-gauge protocol, regardless of testing order and included ascending isometric contractions, culminating with one MVIC. During these trials, the participants were given verbal and visual feedback regarding performance and education was implemented to avoid confusion or troubleshoot positioning. A visual target (120 N) was provided, and participants were instructed to reach and hold this target. The initial force target is implemented to prevent participants from using countermovement or excessive body movement to initiate the contraction, potentially altering rapid force expression measures.[1,6] After familiarization, participants were given a five-minute rest before the data collection initiation. Participants were instructed to contract "fast and hard". The term '*fast*' in "fast and hard" was consistently emphasized throughout all testing occasions.

After familiarization, participants were randomly placed into protocols via a random number generator. Participants were told to achieve the pre-tension state and maintain this force for two seconds by slowly extending the knee into the strap while observing the force-time curve on the monitor. For both devices, participants then performed three contractions at 30% of perceived MVIC, two contractions at 60% of perceived MVIC, one contraction at 90% of perceived MVIC, and one contraction at 100% of perceived MVIC. For the three maximal recorded trials, the participants were once again asked to slowly extend their knee to obtain a steady force curve before the primary researchers began a countdown of "3-2-1-Go-Go-Go-Go-Go-Stop". Participants were instructed to start the MVIC immediately after "1".

Due to the brief contraction durations, the rest between repetitions was set from 10 to 30 seconds following the previous protocols.[15] The output was visually inspected for large deviations in force production (>250 N from prior trials), notable countermovement in the output, or any inconsistencies in the pre-tension state, any false trials removed, and the subject ask to repeat the trial before progressing. Participants completed three trials of each protocol with the maximum values used for analyses. Rest was set at 10-30 seconds based on participant preference.[15]

DATA PROCESSING

Raw, unfiltered force-time data was exported for subsequent analysis in 'comma separated value' format. Using a custom algorithm, the dominant leg data were imported and analyzed in MATLAB (MathWorks, Natick, MA). Each trial was trimmed in length to include a pre-tension period of at least 0.5 seconds, force onset, the isometric contraction for at least one second, and a force offset. The onset of force was defined as an increase in a force greater than three standard deviations (3 SD) of force calculated from the 350 ms pre-tension window within one second before the contraction.[1,17,18] Outputs were visually assessed for methodological outliers (e.g., extreme forces or spikes that were clearly not accurate representations of human capacity), which were removed from the analysis. Methodological outliers were removed on two, and four occasions for the isokinetic dynamometer and strain-gauge devices, respectively. PF was determined as the absolute maximum force recorded during the two-second contraction. All other variables of interest were then determined from within the time interval created by the 20-80% peak force thresholds, as described by Cobian et al. (2017) and Dudley-Javoroski et al. (2008).[18,19] $RFD_{2080}$ was the average slope over the epoch (force/time), and $IMP_{2080}$ was the area under the force-time curve during the 20-80% window. PRFD was calculated using a 10 Hz, 4$^{th}$ order low-pass Butterworth filter.

STATISTICAL ANALYSIS

Data cleaning was conducted using RStudio IDE (Version 1.4.869, RStudio, PBS). Outlier analysis was conducted using intrasession, intra-subject z-scores. Any values greater than 3 SD were removed from the analysis.

Jeffrey's Amazing Statistics Program (JASP) software (version 0.16, Amsterdam, Netherlands) was used for statistical analysis. The statistical analysis explored the validity of the between the isokinetic dynamometer and strain-gauge protocols. Each subject's trials for each protocol were averaged. Further, if the subject did not participate in all protocols, they were also removed from all analyses. The normality of averaged values was confirmed using the Shapiro-Wilks test for each protocol.

Normality was assessed using the Shapiro-Wilks test and visually assessed with Q-Q plots. A Wilcoxon signed-rank test was used to compare protocols (isokinetic dynamometer, plinth+strain-gauge) as normality was not confirmed for PRFD ($p \leqslant 0.050$) and $RFD_{2080}$ ($p \leqslant 0.020$). Qualitative descriptors of standardized Cohen's *d* effect sizes (ES) with 95% confidence intervals (95%CI) were assessed and reported using these criteria: trivial <0.20, small 0.20–0.49, moderate 0.50–0.79, large >0.80.[20] Additionally, Pearson's *r* correlation coefficients were determined and interpreted as: 0-0.10 trivial, 0.10-0.30 small, 0.30-0.50 moderate, 0.50-0.70 large, 0.70-0.90 very large, and >0.90 nearly perfect. 95%CIs were calculated for the correlational data by simulating 1000 bootstrapped samples. Finally, Bland-Altman analyses with 95%CI were used to further understand the difference between paired kinetic variables to the pair's mean across different protocols. All statistical significance was established a priori at $p<0.05$. 95%CIs are reported in [square brackets] in-text.

# RESULTS

The eight men were 30.2±6.8 years old, 173±3.2 cm tall, 84.4±10.9 kg in body mass, and had a shank length of 33.7±3.2 cm. The six females were 33.2±6.7 years old, 161±5.5 cm tall, 61.7±7.5 kg in body mass, and had a shank length of 34.2±1.3 cm. Summary (mean, standard deviation

**Table 1. Mean and standard deviation for each kinetic variable for both protocols with standard error and 95% confidence intervals**

| Variable | Isokinetic dynamometer | Plinth + strain-gauge | Standard error [95% CI] | Effect size [95% CI] | *p*-value | % Δ |
|---|---|---|---|---|---|---|
| PF (N) | 565 ± 143 | 537 ± 117 | 24 [-34.2, 88.8] | 0.26 [-0.32, 0.70] | 0.426 | -5.0 |
| PRFD (N/s) | 3677 ± 1573 | 3327 ± 1192 | 286 [-341, 958] | 0.35 [-0.22, 0.75] | 0.268 | -9.5 |
| $RFD_{2080}$ (N/s) | 2410 ± 1047 | 2351 ± 878 | 264 [-435, 541] | -0.03 [-0.55, 0.51] | 0.952 | -2.5 |
| $IMP_{2080}$ (N/s) | 33.2 ± 13.3 | 30.3 ± 10.3 | 2.95 [-4.27, 9.77] | 0.20 [-0.37, 0.66] | 0.542 | -8.7 |

PF = peak force; PRFD = peak rate of force development; RFD = rate of force development; IMP = impulse. CI = confidence interval. Effect size = Cohen's *d*. Statistics are from Wilcoxon signed-rank tests.

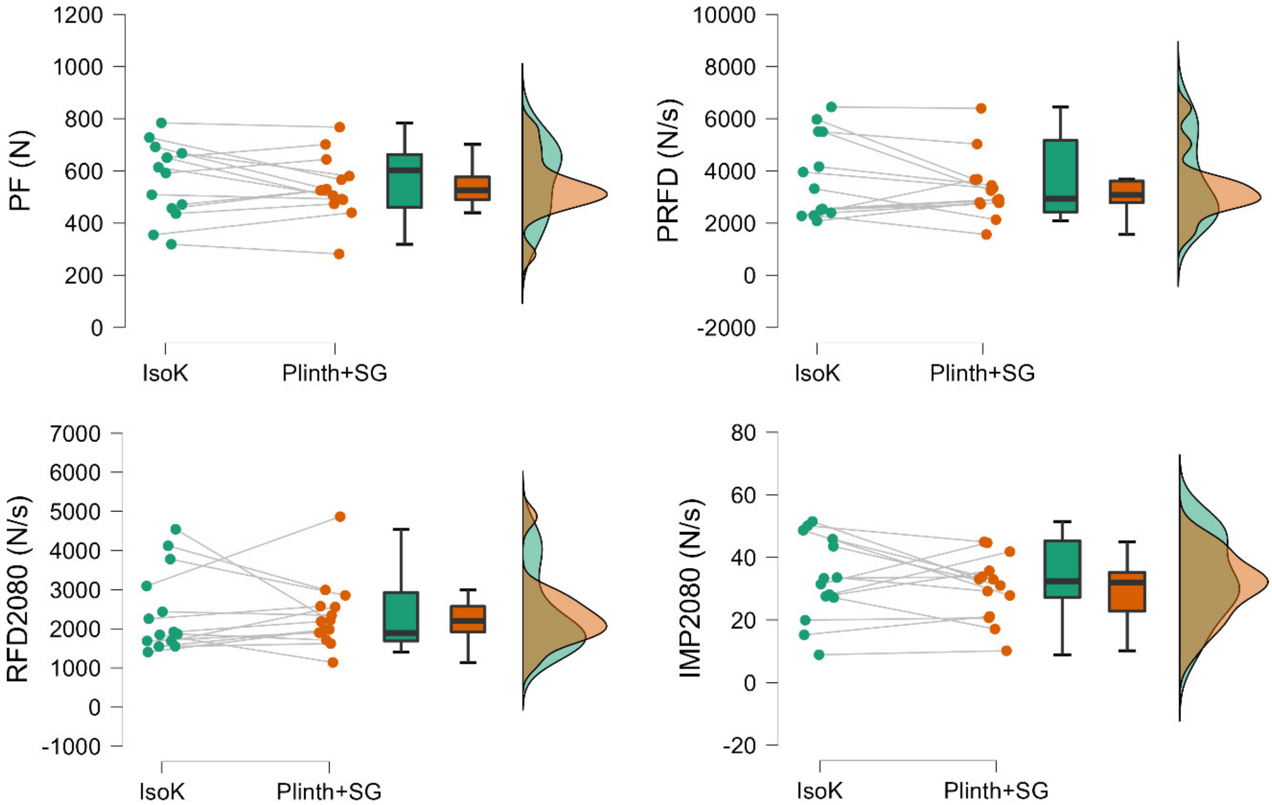


**Figure 2. Raincloud plots for peak force (PF); peak rate of force development (PRFD); rate of force development from 20-80% of onset to PF (RFD2080); and impulse from 20-80% of onset to PF (IMP2080).**

N=newtons, N/s=newton seconds.

[SD]) and Wilcoxon signed-rank test (standard error [SE], ES, p-values) can be observed in Table 1. All variables had higher mean and larger SDs when assessed with the isokinetic dynamometer versus the plinth and strain-gauge, however, these were not statistically significantly different.

Raincloud plots for each kinetic variable collected with each protocol can be observed in Figure 2. No significant or meaningful differences between the protocols were detected for PF (ES=0.26 [-0.32, 0.70], $p$=0.426), PRFD (ES=0.29 [-0.22, 0.75], $p$=0.27), $RFD_{2080}$ (ES=-0.03 [-0.55, 0.51], $p$=0.952), or $IMP_{2080}$ (ES=0.29 [-0.37, 0.66], $p$=0.542).

Pearson's $r$ correlations (Figure 3) detected very large significant between-protocol correlations for PF ($r$=0.77 [0.40, 0.92], $p$=0.001) and PRFD ($r$=0.73 [0.34, 0.91], $p$=0.003). Small and moderate non-significant correlations were found for $RFD_{2080}$ ($r$=0.48 [0.23, 0.84], $p$=0.079) and $IMP_{2080}$ ($r$=0.59 [-0.04, 0.85], $p$=0.060), respectively.

Bland-Altman plots (Figure 4) show acceptable bias for all variables as no data points fell outside of the 95%CI. However, while PF or PRFD were found to have no obvious bias, $RFD_{2080}$ and $IMP_{2080}$ were found to have greater between-protocol differences in high-performing participants.

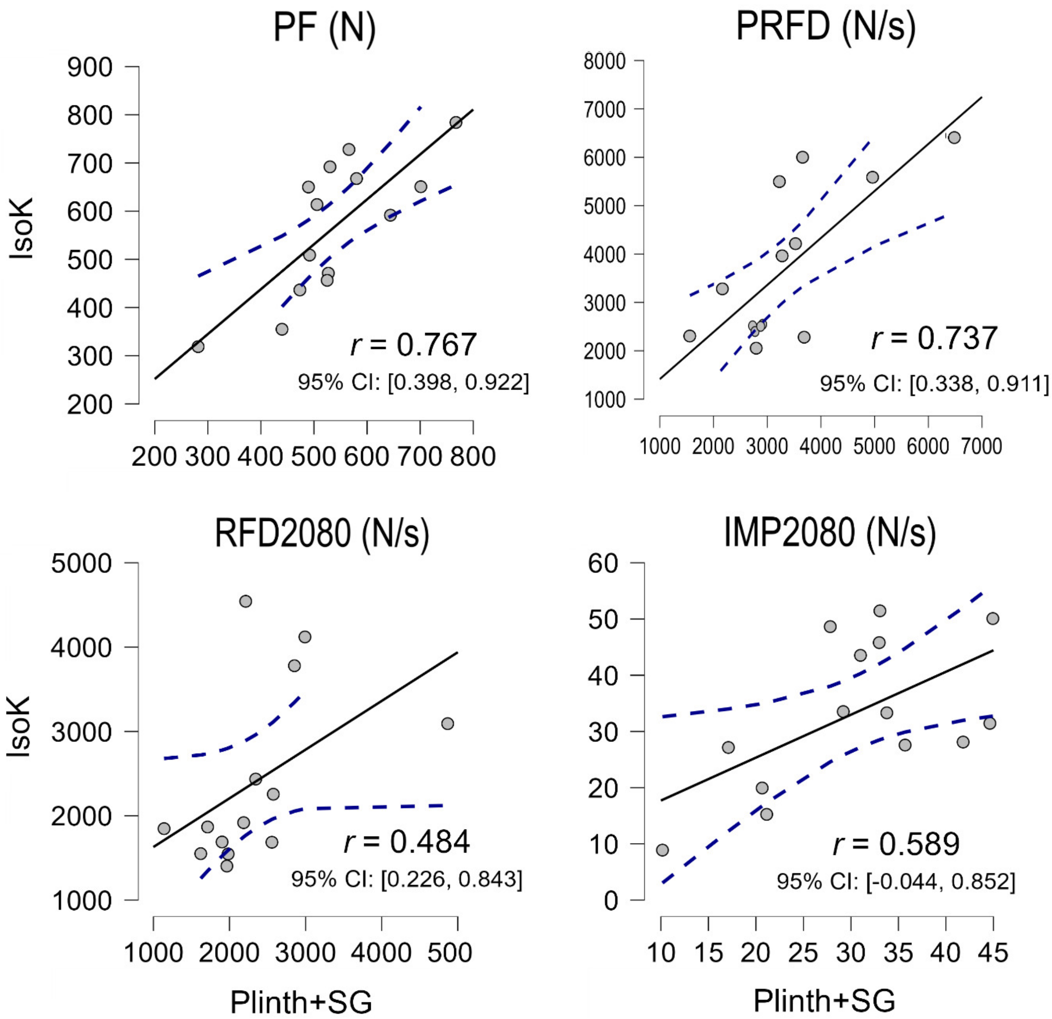


**Figure 3. Pearson's *r* correlation coefficient scatter plots between the isokinetic dynamometer (IsoK) and treatment plinth with strain-gauge (Plinth+SG) for peak force (PF); peak rate of force development (PRFD); rate of force development from 20-80% of onset to PF (RFD2080); and impulse from 20-80% of onset to PF (IMP2080).**

## DISCUSSION

The aim of this study was to investigate the use of a strain-gauge as a clinically practical alternative to an isokinetic device in investigating knee extension kinetics. Typical (PF, PRFD) and novel ($RFD_{2080}$, $IMP_{2080}$) analyses were implemented. Findings included no significant or large differences between the commonly used isokinetic dynamometer and the commercial strain-gauge for any variable. Additionally, the data variability was smaller when utilizing the strain-gauge compared to the isokinetic dynamometer. Very large significant correlations were found between protocols for PF and PRFD, though correlations were small, moderate, and non-significant for the $RFD_{2080}$ and $IMP_{2080}$. Finally, no explicit biases were detected via Bland-Altman analysis. Therefore, we suggest that the practical and affordable strain-gauge and treatment plinth set-up can be used instead of an isokinetic dynamometer for evaluating PF and PRFD in clinical, sports performance, and research settings.

No significant differences (all $p \geqslant 0.268$, ES$\leqslant 0.35$) were found between the two measurement devices across all four variables (PF, PRFD, $RFD_{2080}$, and $IMP_{2080}$) of interest. Although no statistically significant differences were found between devices for the variables of interest, these findings concerning mean and standard deviation and interquartile ranges were observed. Slightly greater kinetic outputs (PF=5.0% and PRFD=9.5%, $RFD_{2080}$=2.4%, $IMP_{2080}$=8.7%) were observed for the isokinetic dynamometer when compared to the strain-gauge. However, the clinical interpretation of these percentage differences is not certain. Also noteworthy was the greater variability (SD) for all four variables on the isokinetic dynamometer than the strain-gauge, which is also apparent when visually inspecting the distributions (Figure 2). This could be explained as the padding on the plinth table was more rigid than on the dynamometer, and the kicking strap was not padded to the degree of the isokinetic dynamometer. Therefore, participants may have felt more comfortable and willing to contract with full effort on the isokinetic dynamometer. However, the isoki-

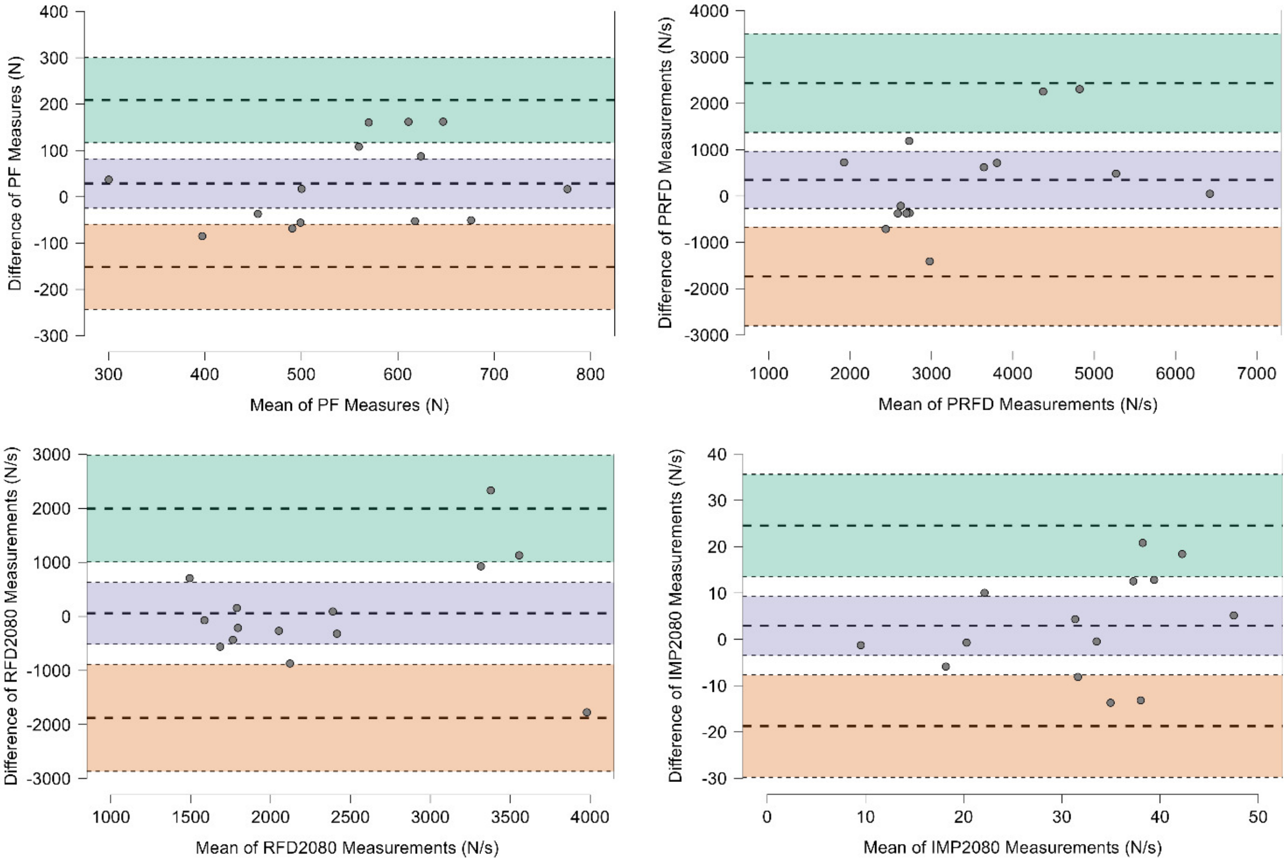


**Figure 4. Bland-Altman plots for peak force (PF); peak rate of force development (PRFD); rate of force development from 20-80% of onset to PF (RFD2080); and impulse from 20-80% of onset to PF (IMP2080).**

Green band = 95% confidence intervals for the mean difference + 1.96 standard deviations; purple band = 95% confidence intervals for the mean difference; pink band = 95% confidence intervals for the mean difference – 1.96 standard deviations.

netic device padding also potentially leads to greater variability in performance and output.

A correlational analysis was also performed to further compare device output and determine device interchangeability for practitioners who may desire switch devices without losing their current database. Very large between-device correlations were found for PF ($r$=0.77, $p$=0.001) and PRFD ($r$=0.73, $p$=0.003), suggesting practitioners could switch between isokinetic dynamometers and the strain-gauge device without losing their current data-set. However, $RFD_{2080}$ ($r$=0.48, $p$=0.079), and $IMP_{2080}$ ($r$=0.59, $p$=0.060) had lower and non-significant between-device correlations. Therefore, practitioners should not compare $RFD_{2080}$ and $IMP_{2080}$ results if switching devices. Additionally, while intra-session $RFD_{2080}$ and $IMP_{2080}$ measures collected with the present strain-gauge at 90° knee angles are moderately reliable intra-session (ICC=0.79-0.93, CV=11.4-22.1%),[14] inter-session variability (ICC=0.48-0.88, CV=10-24.5%)[13] demonstrating that relatively large changes must occur for practitioners to be confident that a real improvement (or decrement) has happened.

Finally, Bland-Altman plots were explored, and demonstrated no statistical increase or decrease in bias proportional to the mean values for all four variables. Therefore, high and lower performers can be assessed similarly using the isokinetic dynamometer and plinth with strain-gauge protocols. However, $RFD_{2080}$ and $IMP_{2080}$ did have visually greater bias with high performers (Figure 4), which leads to the question whether statistical biases would occur with elite strength athletes or others with extraordinary knee-extension kinetics. Regardless, when viewed in combination with previous findings, $RFD_{2080}$ and $IMP_{2080}$ should be used with caution based on moderate to poor reliability[14] and inter-session variability.[13]

## LIMITATIONS

While the aims of the study were completed, the study is not without limitations. The first and most obvious is the relatively small sample size of a relatively homogenous population. Similarly, the sample size makes understanding the potential biases between high- (e.g., athletes), and low- (e.g., clinical) performing populations difficult. Secondly, nuances in collecting rapid force variables are challenging to eliminate, once again exacerbated by the limited sample size. This study utilized a pre-tensioned state before contraction initiation, which can be difficult for some participants. The same contractions also analyzed maximal and rapid force production, increasing variability when compared to using separate rapid and ramping contractions to determine RFD and PF, respectively.[1] Therefore, it may have been beneficial to utilize brief and ramping contractions to assess rapid and maximum force production, respectively.[1] Rest between maximal contractions were self-selected between 10-30 seconds. Therefore, it is plausible that some participants may have performed better or worse on each device based partially on fatigue or post-activation potentiation effects. However, this was likely minimal as participants would likely self-select similar rest periods for both devices. This study compared a single isokinetic dynamometer and a single strain-gauge, and therefore cannot conclusively determine that all dynamometer or strain-gauge manufacturers are similar. Finally, readers should be cognizant that single joint isometric testing, while primarily valuable in rehabilitation contexts, should likely progress to, or be used alongside dynamic multi-joint assessments.

## CONCLUSION

The isokinetic dynamometer is often the standard in open chain force data capture in physical medicine. However, the device's cost and portability often limit its use in clinical settings. The results of the present study indicate that the treatment plinth and strain-gauge combination can be used to produce valid maximal and rapid force measurements at a reduced cost and improved practicality when compared to an isokinetic dynamometer. The study's overall findings support using the strain-gauge as a suitable alternative to the isokinetic dynamometry for measuring PF and PRFD. However, strain-gauge testing of $RFD_{2080}$, and $IMP_{2080}$ should be used with caution.

## CONFLICT OF INTEREST

The strain-gauge and software were developed, in part, by some of the authors of this manuscript with the end goal of commercialization.

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