RELIABILITY OF LOW-COST PORTABLE FORCE PLATFORMS FOR MEASURING VERTICAL STIFFNESS DURING RUNNING

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Ground reaction force (GRF) can provide useful information such as vertical stiffness (K_{vert}) to practitioners working with runners and sprinters, but high equipment costs are hindering applied research. Low-cost portable force platforms may be a useful alternative to traditional biomechanical equipment. Moderately trained runners (n = 9) completed overground running trials at various speeds (2.15-5.78 m/s), K_{vert} was determined, and a linear regression was used to characterize the relationship between K_{vert} and running speed. The results showed moderate to high correlation (r^2 = 0.54 to 0.87). At 3.9 m/s (14 km/h), the widest regression model confidence interval was 4.4%, which shows this procedure likely provides adequate reliability. Future research should continue to investigate the use of low-cost portable force platforms for measuring running GRF.

Key words: Ground reaction force, spring-mass model, biomechanics

INTRODUCTION: Ground reaction force (GRF) characteristics appear to provide an abundance of useful information on the physiological and technical abilities underlying running and sprinting (Burns et al., 2021; Clark et al., 2017; Maloney & Fletcher, 2021). More applied research is need, but the force platforms and instrumented treadmills used in this research are expensive, so progress has been limited. Low-cost, portable force platforms may offer a more economical option to increase the volume of applied research to meet the needs of practitioners. Studies with larger sample sizes, wider range of speeds/abilities, and longitudinal design are needed (Serpell et al., 2012; Struzik et al., 2021).

Vertical stiffness (K_{vert}), the ratio of maximum vertical GRF and maximum vertical displacement of the center of mass (Serpell et al., 2012), is one of the more promising quantities derived from GRF (Maloney & Fletcher, 2021). Past research has shown that K_{vert} increases with running speed (Arampatzis et al., 1999; Brughelli & Cronin, 2008) and is positively correlated with running economy (Dalleau et al., 1998; Heise & Martin, 2001; Zhang et al., 2022) and performance level (Burns et al., 2021). Greater vertical stiffness seems to promote elastic energy utilization, reducing energy demand and improving performance (Struzik et al., 2021).

A growing body of literature supports the use of neuromuscular training like resistance and plyometric training to enhance endurance performance by improving running economy (Barrie, 2020). Concurrent endurance and neuromuscular training, however, can interfere with each other, limiting training adaptation (Doma et al., 2019). Further optimization of concurrent training is needed to maximize performance. Vertical stiffness may help practitioners identify athletes most in need of neuromuscular training, so that training can be targeted to individual needs, thus minimizing training interference. More research is needed to better understand how neuromuscular training to improve strength, power, and elasticity impact K_{vert}.

Instrumented treadmills are often used to study K_{vert} (Burns et al., 2021; Morin et al., 2007; Zhang et al., 2022), however some studies have compared overground and treadmill running (Kluitenberg et al., 2012; Morin et al., 2005) and shown that both are reliable. Instrumented treadmill makes it possible to capture many consecutive steps in a short period of time, but they are expensive, not mobile, and alter gait. Low-cost, portable force platforms have been studied for use in other areas of sports biomechanics (Peterson Silveira et al., 2017; Sands et al., 2020) and may be appropriate for running too.

The objective of this study was to investigate the reliability of K_{vert} as a function of running speed for an overground running procedure using low-cost portable force platforms. The results will be used to determine if such a procedure is suitable for future studies to investigate the relationships between K_{vert} and running performance, identify potential improvements to the procedure, and estimate minimum detectable differences.

METHODS: Data were collected from nine moderately experienced runners (4 female, 5 male) with a wide range of abilities. Overground running trials were completed across force platforms surrounded by a portable wooden runway (5.6x0.8x0.05 m) on an indoor track. Each trial consisted of an approximately 30-m long approach to encourage typical running form. Trials were accepted if the subject made contact entirely on the force platforms and did not make any obvious adjustments to gait near the force platforms. Subject completed approximately twenty-five trials over a range of running speeds (2.15-5.78 m/s). Speed was monitored by optical timing gates (Brower, Draper, UT, USA). Before participation, subjects gave written informed consent and completed a pre-participation health questionnaire. This study was approved by the (institution name removed) Institutional Review Board.

GRF was sampled at 1000 Hz using two force platforms (Pasco PS-2142, Roseville, CA, USA) placed next to each other to provide a 0.70 x 0.35 m surface for foot contact. Data were filtered using a fourth-order, zero-phase-shift, Butterworth filter with a cutoff frequency of 25 Hz and ground contact was defined when the vertical GRF exceeded 40 N (Clark et al., 2017). Vertical stiffness was calculated using: $K_{vert} = F_{max} \cdot \Delta y^{-1}$, where F_{max} is the peak vertical GRF during foot contact and Δy is the vertical displacement of the center of mass at its lowest point, determined from the second integral of vertical GRF (Serpell et al., 2012).

A linear least squares regression was conducted to characterize K_{vert} as a function of running speed. Regression model slope and K_{vert} at 3.9 m/s (14 km/h) were determined for each subject along with 95th-percentile confidence intervals ($CI_{95\%}$). Intraclass correlations (ICC) were computed to compare inter- and intrasubject variation in K_{vert} results.

RESULTS: A total of 247 trials were recorded during data collection. Two trials with large residuals were removed because they were believed to have been caused by alterations in running technique, leaving 245 trials for analysis. Moderate to high correlations were found between K_{vert} and running speed (Figure 1) for all subject ($r^2 = 0.54$ to 0.87, $p < .001$). K_{vert} values at 3.9 m/s varied from 24.8 kN/m to 43.4 kN/m with an average of 35.4 kN/m, (Figure 2). The $CI_{95\%}$ of the models ranged from ±0.459 kN/m to ±1.13 kN/m with an average of 0.734 kN/m. The ICC for regression model predicted K_{vert} at 3.9 m/s was $r^2 = 0.99$. The regression line slopes varied from 3.76 to 11.4 kN/m per m/s with an average of 6.76 kN/m per m/s (Figure 2). The $CI_{95\%}$ varied from 13.8% to 39.7% of the respective mean value, with an average of 21.9%. The ICC for regression model slope was $r^2 = 0.89$.

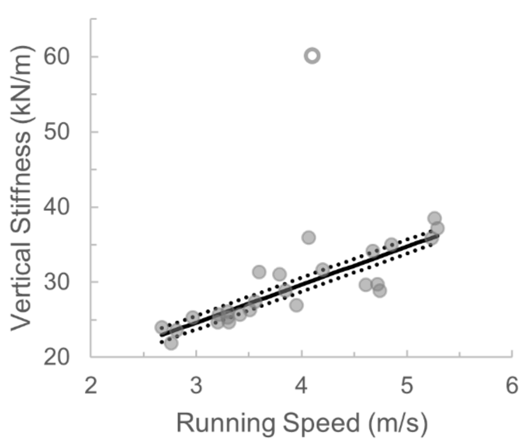
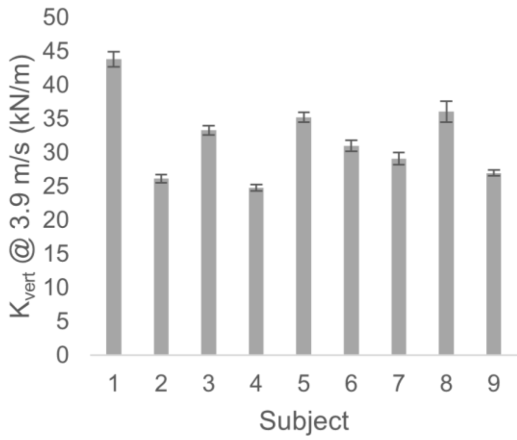


Figure 1: K_{vert} vs. speed for one subject. Filled circles are data points included in the model, the hollow circle is the removed outlier. Lines represent the regression model mean (solid) and $CI_{95\%}$ (dash).



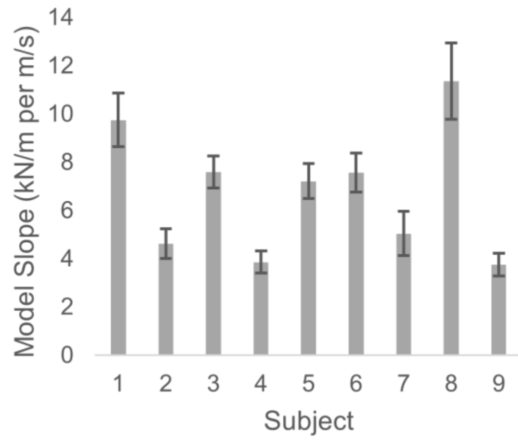


Figure 2: Vertical stiffness (K_{vert}) at 3.9 m/s (left) and regression model slope for each subject (right). The error bars represent $CI_{95\%}$.

DISCUSSION: The results of this study support the use of low-cost portable force platforms for determining K_{vert} for running, though some refinement of the methods may lead to further improvement in measurement reliability. Moderate to high correlations were found between K_{vert} and running speed for all subject and ICCs were high for both regression model slope and K_{vert} at 3.9 m/s. For K_{vert} at 3.9 m/s, the widest $CI_{95\%}$ for any subject was ±4.4% of the modeled value, which suggests at worst it should be possible to detect a difference between two subjects or change over time of 8.8%. For most of the subjects, a difference or change of approximately 5% should be detectable. Greater variability was observed in regression model slopes; however, it may still be possible to detect differences or changes over time. The variability between subjects was still substantially greater than that observed within subjects.

While the methods presented in this study have demonstrated adequate measurement reliability for comparing regression model slope and K_{vert} values at a moderate speed, modifications could lead to improvements in reliability. One potential source of intrasubject variability is that subjects may have been making subtle adjustments to their gait close to the force platforms to hit the target. Adding a third force platform would increase the size of the target and may reduce variability. Teaching subjects to use check marks on their approach (i.e., like many long jumpers use) could also improve variability by encouraging smaller adjustments earlier in the approach. Securing the force platforms to a base may also reduce variability as has been demonstrated for other sports movements (Sands et al., 2020). Another approach would be to increase the number of trials which should reduce the width of the $CI_{95\%}$ of the regression models. Doubling the number of contacts to 50 should decrease the width of the $CI_{95\%}$ by 25%.

Future studies on running GRF should seek to show test-retest reliability of this method and strengthen the relationship between K_{vert} and running performance and investigate changes in K_{vert} over time. Ultimately, prospective experimental studies should be conducted to establish if a cause-and-effect relationship exists among neuromuscular training, running economy, and running performance. A test set-up like the one used in this study could allow these future studies to be conducted using large sample sizes and across a wide range of abilities, which would make their findings more applicable to practitioners.

CONCLUSION: This study presented a low-cost portable test set-up for measuring running GRF and quantifying K_{vert}. The collected data were used to compute a linear regression model for K_{vert} as a function of running speed for each subject. K_{vert} and regression model parameters seemed to have adequate reliability to observe differences in GRF characteristics between groups or changes over time. Future studies should seek to measure test-retest reliability of this method and establish a cause-and-effect relationship between changes in K_{vert} and running performance due to improvements in running economy to aid practitioners in optimizing the use of neuromuscular training for endurance runners and sprinters.

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