Replication Study of the Effect of Different Loading Conditions on Running Mechanics at Different Velocities

Abstract

The aim of this study was to replicate the study titled "*Effect of different loading conditions on running mechanics at different velocities*" by Carretero-Navarro et al., (2019) as part of a large replication project. The selected variable of interest was leg stiffness. Twenty-six recreationally active and healthy males (age: 23 ± 2 years, body mass: 80.20 ± 11.54kg, height: 177.96 ± 6.29cm) participated in two testing sessions, one week apart. Subjects completed an incremental maximal running test on a treadmill to determine their maximal aerobic speed (MAS). During the second session, participants completed nine, one-minute runs under different loading (+0%, +10%, and +20% of body mass using a weighted vest) and speed (60%, 80%, and 100% of their MAS) conditions. A two-way repeated measures ANOVA showed a significant main effect for speed on leg stiffness ($F_{1.7,\ 38.6} = 5.94$, $p = 0.008$, $\eta_p^2 = 0.205$), similar to the original study ($F_{2,\ 24} = 52.577$, $p < 0.001$). However, the replication effect size estimate for speed on leg stiffness ($\eta_p^2 = 0.205$) was significantly smaller than the original ($\eta_p^2 = 0.814$) ($z = 4.56$, $p < 0.001$). The original effect size estimate for the main effect of speed was deemed incompatible with the replication estimate, therefore, the original study was not replicated fully. As there are growing demands for enhancing the quality of sports science research, one should focus on the accumulation of evidence for the effect of speed on leg stiffness to maximize athletic performance.

Highlights:

- This study is part of a larger replication effort, and specifically aimed to replicate the study "Effect of different loading conditions on running mechanics at different velocities" by Carretero-Navarro et al. (2019), with respect to leg stiffness.
- The replication effect size estimate was significantly smaller than the original and therefore was not considered fully compatible with the original paper. However, both studies report a significant main effect for the repeated measures ANOVA.
- The study emphasized the need for a focus on accumulating research evidence using more replication efforts, as well as increased transparency of reporting full results in the literature.

Key Words: replication, leg stiffness, load, speed, running mechanics

Introduction

The credibility of a scientific claim is established with further evidence when the same results can be replicated using new data (Schmidt, 2009). Replication is defined as retesting a claim using the same analyses with new data (Nosek and Errington, 2020), and is considered to be the cornerstone of science (Simons, 2014). The purpose of replication is to validate results and assess their reliability, with the aim of increasing or decreasing the degree of confidence in the originally reported results (Simons, 2014). Due to the need for replicable and reproducible results to drive scientific progress, one might expect replication to be a prominent part of scientific practice, but it is not (Schmidt, 2009). In the majority of scientific disciplines, few direct replications have been studied to date. Given that the replication of empirical results is a key component of the scientific method, such failures weaken the credibility of hypotheses that rely on them and may call into question significant portions of scientific knowledge.

Researchers are not incentivised to replicate studies as novel or statistically significant findings are typically prioritised in journals (publication bias; Nissen et al., 2016). Furthermore, increasing academic pressure to produce new discoveries for career success contributes to engagement in questionable research practices (Chambers *et al.*, 2014). Growing awareness of methodological issues in science emerged due to difficulty replicating the results of numerous scientific investigations in different fields (Open Science Collaboration, 2015; Errington *et al.*, 2021). In psychology, a "replication crisis" was declared due to a replication rate of 36% of 100 studies with the mean effect size amounting to approximately half that of the original studies (Open Science Collaboration, 2015). A similar concerning replication rate of 46% of 50 studies was reported in cancer biology (Errington *et al.*, 2021). Due to the crossover with the psychological field, there is reason to believe that replication issues may be present for the sport and exercise sciences, but this requires further investigation (Murphy *et al.*, 2023).

Like other research fields, sport and exercise science is susceptible to questionable research practices which are estimated to be as high as 50% (Büttner *et al.*, 2020), although further research is needed. There is however clear evidence of low statistical power, small sample sizes, and a lack of transparency in reporting in our field (Heneghan *et al.*, 2012; Halperin *et al.*, 2018). Collectively, these issues may increase the likelihood that a statistically significant effect is a false positive, or inflated, which is likely to affect its replicability and thus, validity (Mesquida *et al.*, 2022). To date, few attempts have been made to examine the replicability of sport and exercise science, therefore, hindering the advancement of the field (Halperin *et al.*, 2018; Murphy *et al.*, 2023). Therefore, a collaborative replication project has been undertaken in sports and exercise science by the Sports Science Replication Centre

(SSRC) with the aim of evaluating the overall replicability of published research (Murphy *et al.*, 2023). This project created a selection protocol to replicate studies in a randomised and unbiased manner (Murphy *et al.*, 2023). As per the selection protocol, we were assigned the study titled *"Effect of different loading conditions on running mechanics at different velocities"* by Carretero-Navarro et al., (2019) which investigated the effect of different loading conditions and different velocities on running mechanics. For this replication, we are specifically interested in the effect of speed on leg stiffness.

It is argued that vertical and leg stiffness are regarded as the most relevant characteristics of the spring-mass model (Cavagna *et al.*, 1988; Mcmahon and Cheng, 1990; Cavagna, Legramandi and Peyré-Tartaruga, 2008; Carretero-Navarro *et al.*, 2019). Leg stiffness describes the ratio of the peak ground reaction force in the spring to the maximal leg compression assessed in the middle of the stance phase (Cavagna *et al.*, 1988; Mcmahon and Cheng, 1990; Cavagna, Legramandi and Peyré-Tartaruga, 2008; Silder, Besier and Delp, 2015). The stiffness of a body is a quantitative measure of its elastic qualities and determines its capacity to store potential elastic energy (Butler, Crowell and Davis, 2003). Therefore, leg stiffness determines the human body's interaction with its environment and may have a substantial influence on running mechanics and running economy (Farley and González, 1996; Ferris, Louie and Farley, 1998). As load and exercise intensity increase the recruitment of motor units, load and speed are key factors that may influence the spring mass model, thereby leg stiffness, and is of particular importance to the study being replicated (Carretero-Navarro *et al.*, 2019).

The effectiveness of elastic energy storage and reutilisation while running is constantly optimised as a result of the adjustment of leg stiffness at different running velocities to account for the impact of landing (Farley *et al.*, 1991; Dalleau *et al.*, 1998; Kyröläinen, Belli and Komi, 2001). Silder, Besier and Delp, (2015) reported an increase in leg stiffness during running when wearing a weighted vest with an additional mass of 10% of body mass (BM). However, to the best of our knowledge, Carretero-Navarro et al., (2019), using an indirect estimation of stiffness, were the first to test the interaction of different loading, and speed conditions on running kinetics and kinematics, in which they observed an increase in leg stiffness as a result of speed, but no change as a result of additional load.

Therefore, the aim of this study is to conduct a close replication of the study by Carretero-Navarro et al., (2019) specifically with respect to the variable "leg stiffness" and the significance, direction, and effect size compatibility. Based on previous research and the established effects of load and speed on lower limb kinematics, we hypothesise that this study will be compatible with the original.

Methods

Study Design

We used a close replication design for this study (Brandt *et al.*, 2014), using the same methodology as the original study (Carretero-Navarro *et al.*, 2019), as assigned by the SSRC's random selection protocol. Whilst the authors refer to the movement as "velocity", the correct definition is "speed" during treadmill running, and we therefore use the term "speed" throughout this replication. Like the original, this is a within subjects design and participants undertook two testing sessions in the laboratory. Potential methodological differences are described throughout and are available online (https://doi.org/10.17605/OSF.IO/C5ZP3).

Participants

Recruitment for this study was voluntary and potential participants were approached via email, personal contact, or social media. Participants were eligible for this study if they (a) were male, (b) were recreationally active, and (c) were aged between 18 and 30. *A priori* sample size calculations are detailed in the study selection protocol (Murphy *et al.*, 2023) which also states that the replication sample size must be larger than the original sample size. As a result, we doubled the original sample size of 13 to 26 participants for this study as it was the only calculation that was larger than the original (https://doi.org/10.17605/OSF.IO/C5ZP3).

A total of 26 recreationally active and healthy males (age: 23 ± 2 years, BM: 80.20 ± 11.54 kg, height: 177.96cm ± 6.29 cm) participated in this replication study. All participants signed an informed written consent form as well as a PAR-Q form prior to testing. All experimental procedures were carried out in accordance with the last review of the Declaration of Helsinki and testing was approved by the institutional ethics committee. This study was pre-registered on the open science framework (https://doi.org/10.17605/OSF.IO/NFZCE).

Procedures

All participants completed two separate testing sessions, one week apart. In the first testing session, subjects completed an incremental maximal running test on a treadmill to determine their maximal aerobic speed (MAS) (Billat and Koralsztein, 1996). The participants' height and body mass (Seca gmbh & co. 22089 Hamburg, Germany) were recorded prior to beginning testing. The test began with an eight-minute warm-up at 7km/h on the treadmill as per the original study (T170 treadmill, Cosmed, Rome, Italy). The treadmill speed was then immediately increased to 8km/h and participants were instructed to run for one minute. The treadmill speed progressively increased by 1km/h every minute until volitional exhaustion was reached. The highest speed reached in the last completed stage was considered the participant's MAS (Billat and Koralsztein, 1996).

During the second session, participants' body mass was recorded prior to completing a five-minute warm-up, running at 8km/h. The participants were then subjected to nine one-minute runs under different loading (+0%, +10%, and +20% of their BM) and speed (60%, 80% and 100% of their MAS, determined in testing session one) conditions. The nine conditions (3 load X 3 velocities) were randomised for each participant. The different loading conditions were set using a weighted vest, which allowed for adjustments of body mass, with an accuracy of 0.1kg. The weight vests had approximately equal weight in the front and back. The recovery period between each trial consisted of a five-minute seated rest in order to avoid fatigue interactions. Spatiotemporal data was recorded during the last 20 seconds of each of the nine conditions using an opto-electrical device (Optogait®, Microgate S.r.I., Bolzano, Italy), which recorded contact time (Ct), flight time (Ft) and step length (SL) at a frequency of 1000 Hz. The Optogait sensors were placed on either side of the treadmill, as close as allowed to the treadmill belt, in order to collect data as accurately as possible (Figure 1).

Figure 1. Optogait sensors set up on both sides of the treadmill during testing session two.

Data Analysis

The mean values of the 20 second recordings were used for data analysis and to calculate step frequency (SF) as SF = 1·(Ct+ Ft)$^{-1}$. The estimative spring-mass model was used to compute the mechanical leg behaviour during ground contact (Blickhan, 1989; McMahon and Cheng, 1990). For the purpose of this replication, the selected main effect was “leg stiffness”. Therefore, the method validated by Morin, (2005) was used to calculate vertical displacement of the CoM (Δy), changes in leg length (ΔL), peak vertical ground reaction force (Fpeak), vertical stiffness (Kvert), and leg stiffness (Kleg):

$$Fpeak = m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{Ft}{Ct} + 1\right); \text{in } kN \tag{1}$$

$$\Delta y = \frac{Fpeak \cdot Ct^2}{m \cdot \pi^2} + g \cdot \frac{Ct^2}{8}; \text{in } m \tag{2}$$

$$\Delta L = \sqrt{L^2 - \left(\frac{v \cdot Ct}{2}\right)^2} + \Delta y; \text{in } m \tag{3}$$

$$Kvert = \frac{Fpeak}{\Delta y}; \text{in } kN \cdot m^{-1} \tag{4}$$

$$Kleg = \frac{Fpeak}{\Delta L}; \text{in } kN \cdot m^{-1} \tag{5}$$

Statistical analysis

A two-way [load by speed] repeated measures ANOVA was conducted to determine the effects of different loading conditions (0%, +10% and 20% of BM) on running kinematics at different velocities (60%, 80% and 100% of MAS). Results from two participants violated the normality assumptions (as assessed by Shapiro-Wilk test and boxplots) and both outliers were removed from the data set. One data point was also an outlier within a participant and a mean substitution for that variable was used after removal of the other outlier cases. After removal of the two outliers and inclusion of the mean substitution for one variable, normality assumptions were met ($p > 0.05$ in the Shapiro-Wilk test). In these cases where sphericity was not met, the Huynh-Feldt correction was applied. The post-hoc analysis was performed with a

Bonferroni correction. Statistical significance was set at $\alpha \leq 0.05$ for all analyses. Effect sizes were expressed as partial eta squared (η_p^2) and 95% confidence intervals were calculated using the *MOTE* package in *R*. All data was analysed using *R* (version 4.2.1).

Replication Outcomes

For the replication to be deemed a success, it must meet the following criteria: the replication effect must be statistically significant and in the same direction as the original effect, and the original effect size must fall within the 95% confidence interval of the replication effect size. A z-test was also used to determine if the replication and original effect size estimates are statistically different using the *TOSTER R* package (version 0.8.0; Caldwell, 2022). We could not reproduce the effect size estimate from the original study for the effect of speed on leg stiffness ($\eta_p^2 = 0.901$) and the effect of speed on vertical stiffness ($\eta_p^2 = 0.975$) using the reported *F*-values and degrees of freedom, therefore, we computed the effect size estimates ($\eta_p^2 = 0.814$ for the effect of speed on leg stiffness and $\eta_p^2 = 0.964$ the effect of speed on vertical stiffness) and used these for the main comparison. The raw data and code for the replication analyses are available at https://doi.org/10.17605/OSF.IO/C5ZP3.

Results

During the first testing session, mean MAS for the participants was 15.58 ± 1.47km/h. Descriptive results for contact time, flight time, step length and step frequency are reported as mean and standard deviation in Table 1.

****** TABLE 1 HERE*******

Spring Mass Model Behaviour - Leg Stiffness

A two-way repeated measures showed no significant load by speed interaction on leg stiffness ($F_{2.97,\ 68.40} = 0.25$, $p = 0.858$, $\eta_p^2 = 0.011$), nor on the main effect of load on leg stiffness ($F_{2,\ 46} = 1.39$, $p = 0.260$, $\eta_p^2 = 0.057$). However, there was a significant main effect of speed on leg stiffness ($F_{1.7,\ 38.6} = 5.94$, $p = 0.008$, $\eta_p^2 = 0.205$).

When examining the post-hoc differences between speed conditions using a Bonferroni correction, leg stiffness increased significantly from the 60% MAS to 100% MAS condition ($M_{diff} = -0.637$ kN.m^{-1}; 95% CI_{diff} [-1.20, -0.07], $p = 0.023$), and the 80% MAS to 100% MAS condition (M_{diff} = -0.598 kN.m^{-1}; 95% CI_{diff} [-0.98, -0.22], p = 0.002). However, there was no difference between the 60% MAS and 80% MAS conditions (M_{diff} = -0.039 kN.m^{-1}; 95% CI_{diff} [-0.67, 0.59], p = 1.0) (Figure 2).

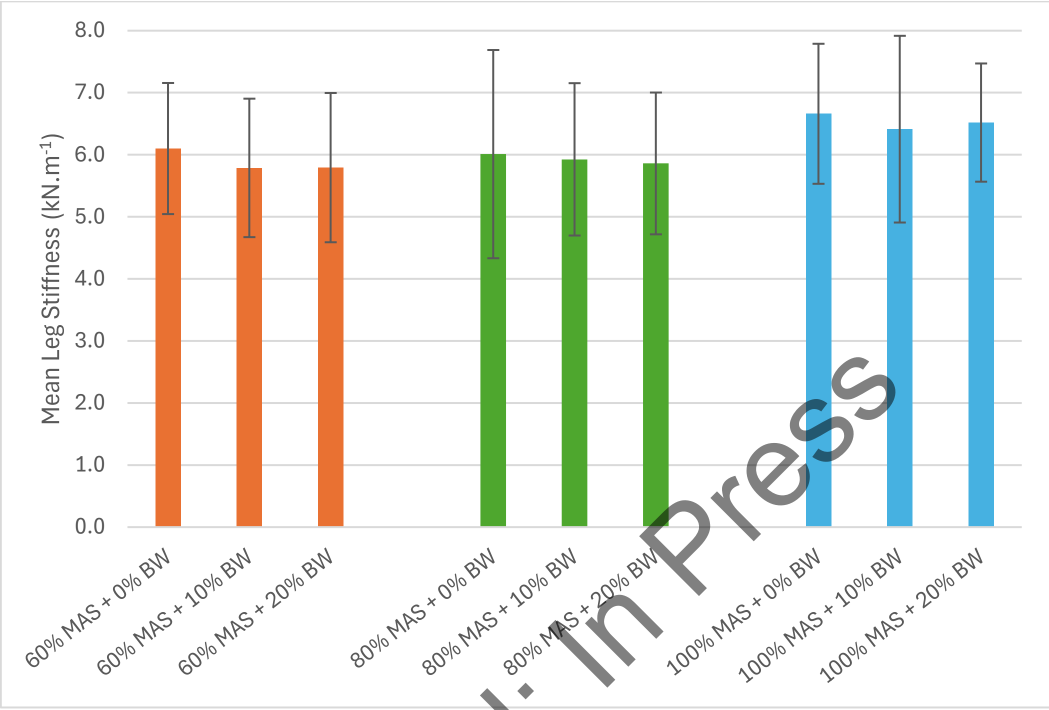

Figure 2. The effects of both speed and load on leg stiffness. Error bars represent standard deviation.

Replication Outcomes - Leg Stiffness

When examining the replication outcome of the main effect for speed, our results showed a significant main effect on leg stiffness ($F_{1.7,\ 38.6}$ = 5.94, p = 0.008, η_p^2 = 0.205), like the original study ($F_{2,\ 24}$ = 52.577, p < 0.001). The z-test for speed indicated that the replication effect size estimate (η_p^2 = 0.205) was significantly smaller than the original effect size estimate (η_p^2 = 0.814) (z = 4.56, p < 0.001). When using the reported effect size estimate for the z-test (η_p^2 = 0.901), the replication effect size estimate was also significantly smaller (z = 5.89, p < 0.001). Therefore, we did not replicate the original effect size estimate, and the replication attempt was deemed partly incompatible.

When examining the main effect for load on leg stiffness, there was a non-significant effect for load on leg stiffness ($F_{2,\ 46}$ = 1.39, p = 0.57, η_p^2 = 0.260), which is similar to the original study where the effect of load on leg stiffness was not statistically significant. The original authors did not report any statistical information for the main effect of load because it was non-significant, therefore, we were unable to compare the direction of results, determine if the original effect size fell within the 95% confidence interval of the replication effect size, or compute the z-test.

Spring Mass Model Behaviour – Vertical Stiffness

We also report the results for vertical stiffness. A two-way repeated measures showed a significant load by speed interaction on vertical stiffness ($F_{3.01, 69.12} = 3.32$, $p = 0.025$, $\eta_p^2 = 0.126$). There was also a significant main effect of load on vertical stiffness ($F_{1.57, 36.19} = 39.37$, $p < 0.001$, $\eta_p^2 = 0.631$) and a significant main effect of speed on vertical stiffness ($F_{1.24, 28.41} = 109.65$, $p < 0.001$, $\eta_p^2 = 0.827$).

When examining the post-hoc differences between speed conditions using a Bonferroni correction, vertical stiffness increased significantly from the 60% MAS to 80% MAS conditions ($M_{diff} = -3.51$ kN.m^{-1}; 95% CI_{diff} [-4.90, -2.13], $p < 0.001$), the 60% MAS and 100% MAS conditions ($M_{diff} = -10.34$ kN.m^{-1}; 95% CI_{diff} [-12.81, -7.87], $p < 0.001$), and the 80% MAS to 100% MAS condition ($M_{diff} = -6.82$ kN.m^{-1}; 95% CI_{diff} [-8.26, -5.39], $p < 0.001$).

When examining the post-hoc differences between load conditions using a Bonferroni correction, vertical stiffness increased significantly from the 0% load to 10% load condition ($M_{diff} = 1.82$ kN.m^{-1}; 95% CI_{diff} [0.86, 2.79], $p < 0.001$), the 0% load to 10% load condition ($M_{diff} = 2.69$ kN.m^{-1}; 95% CI_{diff} [1.86, 3.53], $p < 0.001$), and the 0% load to 10% load condition ($M_{diff} = 0.873$ kN.m^{-1}; 95% CI_{diff} [0.33, 1.41], $p < 0.001$).

Replication Outcomes – Vertical Stiffness

When examining the replication outcome of the main effect for speed, our results showed a significant main effect of speed on vertical stiffness ($F_{1.24, 28.41} = 109.65$, $p < 0.001$, $\eta_p^2 = 0.827$), like the original study ($F_{2, 24} = 319.497$, $p < 0.001$). The z-test for speed indicated that the replication effect size estimate ($\eta_p^2 = 0.827$) was significantly smaller than the original effect size estimate ($\eta_p^2 = 0.964$) ($z = 2.97$, $p = 0.001$). When using the reported effect size estimate for the z-test ($\eta_p^2 = 0.975$), the replication effect size estimate was also significantly smaller ($z = 3.64$, $p < 0.001$). Therefore, we did not replicate the original effect size estimate, and the replication attempt was deemed partly incompatible.

When examining the main effect for load on vertical stiffness, there was a significant effect for load on vertical stiffness ($F_{1.57, 36.19} = 39.37$, $p < 0.001$, $\eta_p^2 = 0.631$), which does not agree with the original study where the effect of load on vertical stiffness was not statistically significant. The original authors did not report any statistical information for the main effect of load because it was non-significant, therefore, we were unable to compare the direction of results, determine if the original effect size fell within the 95% confidence interval of the replication effect size, or compute the z-test.

Discussion

The purpose of the current research was to investigate the replicability of the study by Carretero-Navarro et al., (2019). We were specifically interested in the variable stiffness for replication under different loading and speed conditions in recreationally active, healthy males, which was selected according to a formalised protocol (Murphy *et al.*, 2023). Our results showed a significant effect for speed on leg stiffness similar to the original study, however, we could not replicate the original effect size estimate with the replication effect size significantly smaller than originally reported. In addition, our results showed a non-significant effect of the load on leg stiffness which is consistent with the original study. However, the original study did not report specific statistical values, which limits direct comparison. Due to the significant difference in the effect size estimate, we only consider this study partly compatible with the original. Given that we had the data, we also took this opportunity to report on vertical stiffness, with similar results except for the main effect of load for which we observed a large, significant effect, and the original authors did not.

There are concerns with the existing research practices in sports and exercise science, including publication bias, potentially questionable research practices, poor data sharing, and low statistical power (Caldwell *et al.*, 2020; Mesquida *et al.*, 2022). In addition, lack of reporting transparency is a barrier to replication, as evident in this replication attempt with respect to the statistical results for the "load" main effect. The original sample size was small (n = 13), indicating low statistical power which can reduce the chance of detecting a true effect (a type 2 error; not rejecting the null hypothesis when there is a significant effect) (Button *et al.*, 2013). However, if a statistically significant effect is found with small sample sizes, it is possible that the findings reflect a type 1 error (rejecting the null hypothesis in the absence of a true effect) (Button *et al.*, 2013). Furthermore, underpowered original studies can lead to regression of effect sizes in replication studies with larger sample sizes, impacting replication rates. This is evident in this replication study where the original study reported $\eta_p^2 = 0.901$ (computed $\eta_p^2 = 0.814$) for the effect of speed on leg stiffness, a very large effect, but the replication effect significantly regressed to $\eta_p^2 = 0.205$.

Our findings suggest that increasing speed from sub-maximal to maximal speeds can significantly increase estimated leg stiffness, in line with the original study findings. As previously mentioned, leg stiffness is a mechanical property of the leg that characterizes the relationship between the ground reaction force and the displacement of the centre of mass during locomotion. According to the spring mass model, any change in Fpeak or leg length will have a direct effect on leg stiffness parameters (Blickhan, 1989; McMahon and Cheng, 1990). In the case of this replication cohort, the increase in leg stiffness may be accounted for by a linear increase in Fpeak values as speed increased from 60% MAS through to 100% MAS, as well as an overall increase in leg length changes from 60% MAS through to 100% MAS. It is clear that this is a complex elastic system that is difficult to elucidate, and may be due to several factors including changes in muscle activation patterns, tendon stiffness, and joint kinematics (Günther and Blickhan, 2002; Kuitunen, Komi and Kyröläinen, 2002; Struzik et al., 2021), which were not explored here using this indirect method. Since our findings are in line with those of other studies on the spring-mass model in running (McMahon, Valiant and Frederick, 1987; Blickhan, 1989; McMahon and Cheng, 1990; He, Kram and McMahon, 1991; Farley and González, 1996; Ferris, Louie and Farley, 1998), these results further contribute to existing evidence that leg stiffness increases with increased speed (Kuitunen, Komi and Kyröläinen, 2002; Morin, 2005; Kim and Park, 2011), albeit at a potentially lower effect size than reported.

Consistent with the original study, our results suggest that additional loading has no effect on leg stiffness. Our results contrast with previous studies investigating the effect of load on leg stiffness (Teunissen, Grabowski and Kram, 2007; Silder, Besier and Delp, 2015). These studies reported an increase in leg stiffness when running with additional load, as a result of a simultaneous increase in the peak vertical ground reaction force, and a decrease in the change in stance phase leg length. However, Kramer et al., (2012) and Kuitunen, Komi and Kyröläinen, (2002) reported leg stiffness remained unaltered despite the increase in Fpeak with additional loading . This lack of change may be explained by the ability to adapt joint kinematics in response to the additional load, but the lack of kinematic data limits this discussion here. Different findings could occur as a result of the different methodologies used to compute kinetic and kinematic data in these studies, however, the indirect assessment of leg stiffness in this study has been demonstrated to be valid and reliable (Morin, 2005; Coleman *et al.*, 2012; Pappas *et al.*, 2014). Thus, other factors such as the morphology of the athletes, weight intensity and distribution within the vest, and the variance in speed may also be possible factors causing these discrepancies (Carretero-Navarro *et al.*, 2019). Interestingly, we did see a significant effect of load on vertical stiffness, which aligns more closely with these other studies. Vertical stiffness tends to change more noticeably with added load, this is because vertical stiffness depends directly on the total force applied and the compression of the centre of mass, which is more likely influenced by additional load (Mcmahon and Cheng, 1990; Dalleau *et al.*, 1998). The disagreement with the original study is likely a result of type 2 error, but without direct kinematic measures, we cannot make any direct comparisons.

Despite our best efforts to conduct a replication as close as possible to the original, there were some differences between the two that should be documented. The original study treadmill was an Excite® Run MD (Technogym SpA, Cesena, Italy) but the replication study treadmill was the T170 treadmill (Cosmed, Rome, Italy). The difference in equipment use here may have had a significant effect on the replication outcome, as each treadmill has a different belt stiffnessClick or tap here to enter text.. This factor directly effects leg stiffness (Silder, Besier and Delp, 2015). However, Farley and González, (1996) reported that leg stiffness is adjusted to offset differences in surface stiffness during hopping in place or forward running.

Another factor that could have impacted the results of this replication study was the placement of the Optogait sensors. The original study did not report how the Optogait sensors were placed to accurately measure spatiotemporal variables and were unresponsive to emails. We placed a sensor on either side of the treadmill belt, slightly raised on the foot pads (Figure 1). As the sides were slightly raised off the treadmill belt itself, the device did not always pick up the participants movements at low speeds. Participants had to be encouraged to "lift their feet" as they ran during the 60% MAS condition in order for the sensor to pick up each step. This automatically altered the participants' running mechanics, directly resulting in altered spatiotemporal variables as well as an artificial change in leg length. Therefore, it could have significantly affected the leg stiffness calculation but only at the lower speed. Another limitation of this study was the weight vest used to alter loading conditions. The maximum capacity of the vest was 20kg and therefore, participants had to be excluded if they weighed more than 100kg.

Conclusion

While the findings for the main effect of speed on estimated leg stiffness in this study mirrored those in the original in terms of statistical significance, there was a statistically significant difference in replication and original effect size estimates, and we consider the replication only partly compatible with the original. Specifically, we observed a significantly smaller reported effect size than the original which is a wider concern regularly observed during replication trials. We also saw no agreement within the vertical stiffness comparison under load. The lack of transparency in reporting by the original authors meant the results for load from the two studies could not be compared but did seem to be compatible with respect to significance. This replication study is part of a larger replication project investigating the replicability of sports and exercise science research. This project, and specifically this replication study, should demonstrate the importance of transparency in research reporting and the need to focus on the accumulation of research evidence rather than specific outcomes of independent studies.

References

Billat, L.V. and Koralsztein, J.P. (1996) ‘Significance of the velocity at V02max and time to exhaustion at this velocity’, *Sports Medicine*, 22(1), pp. 90–108. Available at: https://doi.org/10.2165/00007256-199622020-00004.

Blickhan, R. (1989) ‘The spring-mass model for running and hopping’, 22(11), pp. 1217–1227. Available at: https://doi.org/10.1016/0021-9290(89)90224-8.

Brandt, M.J. *et al.* (2014) ‘The Replication Recipe: What makes for a convincing replication?’, *Journal of Experimental Social Psychology*, 50(1), pp. 217–224. Available at: https://doi.org/https://doi.org/10.1016/j.jesp.2013.10.005.

Brumitt, J. and Cuddeford, T. (2015) ‘Current concepts of muscle and tendon adaptation to strength and conditioning.’, *International journal of sports physical therapy*, 10(6), pp. 748–59.

Butler, R.J., Crowell, H.P. and Davis, I.M.C. (2003) ‘Lower extremity stiffness: Implications for performance and injury’, *Clinical Biomechanics*, 18(6), pp. 511–517. Available at: https://doi.org/10.1016/S0268-0033(03)00071-8.

Büttner, F. *et al.* (2020) ‘Are questionable research practices facilitating new discoveries in sport and exercise medicine? The proportion of supported hypotheses is implausibly high’, *British Journal of Sports Medicine*, pp. 1–7. Available at: https://doi.org/10.1136/bjsports-2019-101863.

Button, K.S. *et al.* (2013) ‘Power failure: Why small sample size undermines the reliability of neuroscience’, *Nature Reviews Neuroscience*, 14(5), pp. 365–376. Available at: https://doi.org/10.1038/nrn3475.

Caldwell, A.R. *et al.* (2020) ‘Moving sport and exercise science forward: A call for the adoption of more transparent research practices’, *Sports Medicine*, 50(3), pp. 449–459. Available at: https://doi.org/10.1007/s40279-019-01227-1.

Caldwell, A.R. (2022) *Exploring equivalence testing with the updated TOSTER R package*. Available at: https://orcid.org/0000-0002-4541-6283.

Carretero-Navarro, G. *et al.* (2019) ‘Effect of different loading conditions on running mechanics at different velocities’, *European Journal of Sport Science*, 19(5), pp. 595–602. Available at: https://doi.org/10.1080/17461391.2018.1537378.

Cavagna, G.A. *et al.* (1988) ‘The determinants of the step frequency in running, trotting and hopping in man and other vertebrates.’, *Journal of Physiology*, 399, pp. 81–92. Available at: https://doi.org/https://doi.org/10.1113/jphysiol.1988.sp017069.

Cavagna, G.A., Legramandi, M.A. and Peyré-Tartaruga, L.A. (2008) ‘Old men running: Mechanical work and elastic bounce’, *Proceedings of the Royal Society B: Biological Sciences*, 275(1633), pp. 411–418. Available at: https://doi.org/10.1098/rspb.2007.1288.

Chambers, C.D. *et al.* (2014) ‘Instead of “playing the game” it is time to change the rules: Registered Reports at AIMS Neuroscience and beyond’, *AIMS Neuroscience*, 1(1), pp. 4–17. Available at: https://doi.org/10.3934/Neuroscience.2014.1.4.

Coleman, D.R. *et al.* (2012) ‘Leg stiffness in human running: Comparison of estimates derived from previously published models to direct kinematic-kinetic measures’, *Journal of Biomechanics*, 45(11), pp. 1987–1991. Available at: https://doi.org/10.1016/j.jbiomech.2012.05.010.

Dalleau, G. *et al.* (1998) ‘The spring-mass model and the energy cost of treadmill running’, *European Journal of Applied Physiology and Occupational Physiology*, 77(3), pp. 257–263. Available at: https://doi.org/10.1007/s004210050330.

Errington, T.M. *et al.* (2021) ‘Investigating the replicability of preclinical cancer biology.’, *eLife*, 10, pp. 1–30. Available at: https://doi.org/10.7554/eLife.71601.

Farley, C.T. *et al.* (1991) ‘Hopping frequency in humans: A test of how springs set stride frequency in bouncing gaits’, *Journal of Applied Physiology*, 71(6), pp. 2127–2132. Available at: https://doi.org/10.1152/jappl.1991.71.6.2127.

Farley, C.T. and González, O. (1996) ‘Leg stiffness and stride frequency in human running’, *Journal of Biomechanics*, 29(2), pp. 181–186. Available at: https://doi.org/10.1016/0021-9290(95)00029-1.

Ferris, D.P., Louie, M. and Farley, C.T. (1998) ‘Running in the real world: Adjusting leg stiffness for different surfaces’, *Proceedings of the Royal Society B: Biological Sciences*, 265(1400), pp. 989–994. Available at: https://doi.org/10.1098/rspb.1998.0388.

Günther, M. and Blickhan, R. (2002) ‘Joint stiffness of the ankle and the knee in running’, *Journal of Biomechanics*, 35(11), pp. 1459–1474. Available at: https://doi.org/10.1016/S0021-9290(02)00183-5.

Halperin, I. *et al.* (2018) ‘Strengthening the practice of exercise and sport-science research’, *International Journal of Sports Physiology and Performance*, 13(2), pp. 127–134. Available at: https://doi.org/10.1123/ijspp.2017-0322.

He, J., Kram, R. and McMahon, T.A. (1991) ‘Mechanics of Running Under Simulated Low Gravity’, *Journal of Applied Physiology*, 71(3), pp. 863–870. Available at: https://doi.org/10.1152/jappl.1991.71.3.863.

Heneghan, C. *et al.* (2012) ‘Forty years of sports performance research and little insight gained.’, *BMJ*, 345. Available at: https://doi.org/10.1136/bmj.e4797.

Kim, S. and Park, S. (2011) ‘Leg stiffness increases with speed to modulate gait frequency and propulsion energy’, *Journal of Biomechanics*, 44(7), pp. 1253–1258. Available at: https://doi.org/10.1016/j.jbiomech.2011.02.072.

Kramer, A. *et al.* (2012) ‘Leg stiffness can be maintained during reactive hopping despite modified acceleration conditions’, *Journal of Biomechanics*, 45(10), pp. 1816–1822. Available at: https://doi.org/10.1016/j.jbiomech.2012.04.014.

Kuitunen, S., Komi, P. V. and Kyröläinen, H. (2002) ‘Knee and ankle joint stiffness in sprint running’, *Medicine and Science in Sports and Exercise*, 34(1), pp. 166–173. Available at: https://doi.org/10.1097/00005768-200201000-00025.

Kyröläinen, H., Belli, A. and Komi, P. V. (2001) ‘Biomechanical factors affecting running economy’, *Medicine and Science in Sports and Exercise*, 33(8), pp. 1330–1337. Available at: https://doi.org/10.1097/00005768-200108000-00014.

Mcmahon, T.A. and Cheng, G.C. (1990) ‘The mechanics of running: How does stiffness couple with speed?’, *Journal of Biomechanics*, 23, pp. 65–78. Available at: https://doi.org/https://doi.org/10.1016/0021-9290(90)90042-2.

McMahon, T.A. and Cheng, G.C. (1990) ‘The mechanics of running: How does stiffness couple with speed?’, *Journal of Biomechanics*, 23(SUPPL. 1), pp. 65–78. Available at: https://doi.org/10.1016/0021-9290(90)90042-2.

McMahon, T.A., Valiant, G. and Frederick, E.C. (1987) ‘Groucho running’, *Journal of Applied Physiology*, 62(6), pp. 2326–2337. Available at: https://doi.org/10.1152/jappl.1987.62.6.2326.

Mesquida, C. *et al.* (2022) ‘Replication concerns in sports and exercise science: a narrative review of selected methodological issues in the field’, *Royal Society Open Science*, 9(220946). Available at: https://doi.org/10.1098/rsos.220946.

Morin, J.B. (2005) ‘A simple method for measuring lower limb stiffness during running’, *Journal of Applied Biomechanics*, 21, pp. 167–180. Available at: https://doi.org/10.1007/978-3-319-05633-3_8.

Murphy, J. *et al.* (2023) ‘Proposal of a Selection Protocol for Replication of Studies in Sports and Exercise Science’, *Sports Medicine*, 53, pp. 281–291. Available at: https://doi.org/10.1007/s40279-022-01749-1.

Nissen, S.B. *et al.* (2016) ‘Publication bias and the canonization of false facts’, *eLife*, 5. Available at: https://doi.org/10.7554/eLife.21451.

Nosek, B.A. and Errington, T.M. (2020) ‘What is replication?’, *PLoS Biology*, 18(3), pp. 1–8. Available at: https://doi.org/10.1371/journal.pbio.3000691.

Open Science Collaboration (2015) ‘Estimating the reproducibility of psychological science’, *Science*, 349(6251). Available at: https://doi.org/10.1126/science.aac4716.

Pappas, P. *et al.* (2014) ‘Reliabilities of leg and vertical stiffness during treadmill running’, *Sports Biomechanics*, 13(4), pp. 391–399. Available at: https://doi.org/10.1080/14763141.2014.981853.

Schmidt, S. (2009) ‘Shall we really do it again? The powerful concept of replication is neglected in the social sciences’, *Review of General Psychology*, 13(2), pp. 90–100. Available at: https://doi.org/10.1037/a0015108.

Silder, A., Besier, T. and Delp, S.L. (2015) ‘Running with a load increases leg stiffness’, *Journal of Biomechanics*, 48(6), pp. 1003–1008. Available at: https://doi.org/10.1016/j.jbiomech.2015.01.051.

Simons, D.J. (2014) ‘The value of direct replication’, *Perspectives on Psychological Science*, 9(1), pp. 76–80. Available at: https://doi.org/10.1177/1745691613514755.

Struzik, A. *et al.* (2021) ‘Application of leg, vertical, and joint stiffness in running performance: A literature overview’, *Applied Bionics and Biomechanics*, 2021. Available at: https://doi.org/10.1155/2021/9914278.

Teunissen, L.P.J., Grabowski, A. and Kram, R. (2007) ‘Effects of independently altering body weight and body mass on the metabolic cost of running’, *Journal of Experimental Biology*, 210(24), pp. 4418–4427. Available at: https://doi.org/10.1242/jeb.004481.