Title:

Evaluating dynamic similarity of fixed, self-selected and anatomically scaled speeds in non-linear analysis of gait during treadmill running.

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Highlights

Anatomically scaled speeds result in dynamical similarity of non-linear measures of gait.

Froude speeds provide a legitimate alternative to fixed or self-selected speed in gait analysis.

Healthy subjects adapt their gait to ensure optimal variability when speeds are changed by ±10%.

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Abstract

Objectives

The aim of this study is to evaluate how speed affects non-linear measures of variability. Fixed and self-selected speeds were compared to an anatomically scaled speed calculated based on leg length to evaluate which provided a more reproducible result between subjects.

Methods

Sixteen subjects ran on a treadmill at a fixed, scaled and self-selected speed and at ±10% in each case. Kinematic data were collected for two minutes at 250Hz for each trial. Sample entropy (SaEn) and maximum Lyapunov exponents (LyE) were calculated from the sagittal knee and hip joint angles to evaluate regularity of gait and local stability. These nonlinear measures were compared to evaluate the dynamic similarity of the movement in each case, and to evaluate speed as a confounding variable in non-linear analysis.

Results

An anatomically scaled speed shows more dynamic similarity than a fixed or self-selected speed with the lowest observed coefficient of variation for each measure. This was found to be statistically significant for both nonlinear measures of the hip (SaEn p=0.038; LyE p=0.040). Speed was not found to be a confounding variable in non-linear analysis of running gait of a healthy population ($\eta^2 < 0.05$).

Conclusions

Changes in speed by ±10% do not significantly affect stability and variability of gait for healthy participants, suggesting that they make adaptations to ensure optimal gait variability.

Anatomically scaled speeds provide a more reliable methodology for both linear and non-linear analysis by providing a definitive protocol, suggesting it could replace self-selected or fixed speeds in future research.

Keywords

Non-linear analysis, speed, Froude, running, gait.

1. Introduction

1.1 Gait analysis speed selection

Speed is a potentially confounding variable in gait analysis, with self-selected speeds used to remove any effect of the same fixed speed for each subject biasing the results. Despite several studies comparing treadmill and outdoor walking, and fixed and self-selected speed, there remain conflicting results and a lack of definitive protocol with some papers calling for researchers to “standardize the use of SP TMs [self-paced treadmill walking] … by unifying protocols” (Plotnik et al, 2015).

Despite a lack of defined protocol, self-selected speeds are often used in gait analysis studies, as it allows the participant to choose what they consider to be an optimal speed (Fukuchi et al, 2019). The self-selection of speed is usually done by asking the participant to find a comfortable pace, but this is subjective, and can also vary depending on the distance expected (Plotnik et al, 2015). There may also be bias introduced by the researcher, depending on how they explain the pace required (Brinkerhoff et al, 2019), which also further supports self-selected speeds being unreliable and prone to error.

The common alternative to self-selected speed is to use the same fixed speed for all participants, using pilot testing or normative data, to ensure consistency and reliability (Moissenet et al, 2019). However, despite the advantages of the use of a fixed speed to standardize protocols, using a fixed speed is also problematic as this may not suit participants with different leg lengths. If this is close to a maximal speed for a participant or close to the walk/run transition, this is likely to affect the gait pattern by being uncomfortable for the participant to sustain (Moraiti et al, 2007) and may mask natural gait characteristics and affect study results.

1.2 Dynamic similarity

Self-selected speeds and fixed speeds are problematic, so alternative methods of finding consistent and repeatable speeds may provide more reliable data capture, and standardize the analysis of any effects seen. Originally used in fluid dynamics, the concept of dynamic similarity suggests that geometrically similar objects with the same shape but different sizes will have similar behaviors (Chanson, 2004). This suggests that two differently sized models are similar if scaled, and so can provide a consistent framework to capture data (Villeger, 2014). Studies have considered the importance of ‘standardized’ speed (Queen et al, 2006) but this relates to a fixed speed for all participants, which fails to take anatomical differences into account. Using a speed that potentially results in dynamic similarity allows a more robust approach, maximizing reliability and removing any confounding effect relating to speed. Dynamic similarity would give less variable results between participants, which could potentially resolve the issues identified with self-selected or fixed speeds, as discussed above.

The inverted pendulum model suggests that human locomotion can be represented by a centre of mass oscillating at the end of a straight segment (Cavagna et al, 1977), with centripetal and gravitational forces acting on this centre of mass. The Froude number is a dimensionless number derived from the ratio of the centripetal force and the force due to gravity, and speeds corresponding to the same Froude number would be considered to be dynamically similar (Villeger, 2014). This value is dependent on leg length, gravity and speed, so calculating the speed corresponding to a fixed Froude number allows us to create a potentially dynamically similar speed for each participant. Using a scaled speed based on this Froude number may remove any confounding factor introduced by speed and stature.

1.3 Non linear analysis

Studies comparing self-selected and fixed speeds commonly focus on linear measures such as mean stride length or variance of joint angles (Sloot et al, 2014; Zampeli et al, 2010) rather than non-linear measures such as local dynamic stability. Linear measures can only investigate the magnitude of variability, rather than how this complexity changes over time, and a non-linear analysis approach is required to investigate this temporal, dynamic aspect of variability (Harbourne and Stergiou, 2009). Linear measures may not in themselves be sufficient to fully describe the features of the gait relating to instability and perturbation, and may identify variations as noise rather than a legitimate part of the gait cycle (Stergiou et al, 2004a). Gait patterns are not completely regular, and although periodic in nature have aspects of chaos and unpredictability. Common non-linear analysis methods seek to explore how the system responds to small changes in initial conditions, or local dynamic stability, which can be evaluated with Lyapunov exponents (Wurdeman, 2017), or the nature of the randomness and regularity of the gait pattern, evaluated via sample entropy (Yentes, 2017).

A number of studies have considered non-linear measures and how these change with walking speed (Dingwell et al, 2001; Stergiou et al, 2004; Moraiti et al, 2007; Bruijn et al, 2009). Some studies have shown that a slower walking speed correlates with increased local dynamic stability, and compared different proportions of anatomically scaled speeds (England and Granata, 2007). Recent research shows that speed may be a confounding variable when considering injured participants using non-linear analysis (Nazary-Moghdam et al, 2019) and previous research has recognised this possibility and used a self-selected speed to rule out this effect (Stergiou et al, 2004a; Georgoulis et al, 2006, Moraiti et al, 2007; Zampeli et al, 2010). As discussed earlier, where self-selected speed has been used in these studies, there is no clearly defined protocol to suggest how this has been achieved and standardised.

Where previous studies have considered using Froude numbers to evaluate dynamic stability in running, the comparison has been done with fixed speeds and linear measures (Delattre et al, 2009; Villeger et al, 2014). Other studies have considered walking (Villeger et al, 2015), or walk-run transitions (Kram et al, 1997) again considering linear measures. In each case using a scaled speed resulted in apparent dynamical similarity, but there is a gap in the research considering how the Froude number affects non-linear analysis and comparing this to self-selected speeds.

The aim of this research was to compare non-linear measures of knee and hip kinematic variability at self-selected speed, fixed speed and speed scaled using the Froude number. It was hypothesized that the non-linear analysis measures calculated at the Froude speed would a show reduced between participant variation, and provide a legitimate alternative to the self-selected speed. A secondary aim of the study was to compare the effect of running speed on non-linear measures of gait variability in a healthy population.

2. Methodology

2.1 Subjects

Sixteen subjects (7 male, 9 female) volunteered to take part in this study. Participants were required to be uninjured and healthy, and recreationally active. The average age was 23 years (±3.5), height 1.72m (±0.1), leg length 0.88m (±0.07) and weight 67kg (±14.8). Institutional ethical approval was obtained prior to capturing any data for this study, and the study adheres to the Helsinki Declaration.

2.2 Protocol

All participants completed a pre-exercise health questionnaire and provided informed consent prior to participation. The participants ran on a treadmill (HP Cosmos Mercury, Nussdorf, Germany) and a ten camera Vicon (Vicon, Oxford metrics, Oxford, UK) motion capture system was used to record the movement for each trial. Markers were applied to anterior and posterior superior iliac spines, lateral femoral epicondyles, tibial tuberosities, lateral malleolus, second metatarsal, calcaneus, mid-thigh, and laterally one-third up/down the tibia and thigh - thigh and tibia markers were placed asymmetrically to assist with recognition (Vicon, 2019). The same researcher applied the markers to each participant to reduce risk of error in placement (Milner, 2008). Data values were recorded at 250Hz.

Each participant was given time to warm up and familiarize themselves with running on the treadmill. The participants were given standardized instructions to allow them to self select their speed, this ensured limited bias was introduced into this choice by the researcher (Brinkerhoff et al, 2019). Specifically, each participant was asked to increase the treadmill speed from a set walking pace ($4kmh^{-1}$) to find a running speed that they could comfortably maintain for 20 minutes. During this time the speed was obscured from their view to prevent this affecting their choice. The self-selected speed was always determined before the start of any trials, and without the participant being aware of the value of the fixed and scaled speeds and was carried out by the same researcher to avoid influencing the participant.

The Froude number is based on leg length, but there does not appear to be a clearly defined measure that specifies the anatomical landmarks used for this measurement.

In this study we used the anterior superior iliac spine to medial malleolus, as this is consistent with the Vicon measurement system (Vicon, 2019). As the important factor here is dynamic similarity based on anatomical differences, then consistency of measurement within a trial should ensure a valid comparison between subjects and enable an appropriate conclusion to be reached. The leg length measurement was taken by the same researcher to ensure consistency and accuracy. A fixed speed was selected based on pilot testing the self-selected speed of a small (n=10) sample of the population, this speed corresponded to the median value of this sample, which was 10.6kmh^{-1}. The median Froude number of this sample was 1.0, so this was used for the scaled speed in this study. The transition between walking and running commonly occurs at a Froude number of 0.5 (Hreljac, 1995), so this value also avoids the trials using a speed 10% lower being close to this transition, while also excluding maximal running speeds. The Froude number corresponding to a given leg length L (in m) for a velocity v (in ms^{-1}) is given by:

$$F = \frac{v^2}{Lg}$$

Equation 1

where g is the acceleration due to gravity (Diedrich and Warren, 1995).

Therefore, the speed was calculated via:

$$v = \sqrt{FLg}$$

Equation 2

using an approximate value of g = 9.81ms^{-2} and a Froude number of 1.

Each participant ran for two minutes at their self-selected speed, their Froude speed and the fixed speed and also at speeds 10% lower and higher in each case. The order of the trials was randomized to reduce any training effect and to reduce the effects of fatigue on the stability and regularity of the gait pattern. Participants were not aware of the order or speeds in advance of the trials. Participants could rest between trials for as long as they wanted.

When studies have considered the Froude number previously, they have also included the Strouhal number within the research (Delattre, 2009; Villeger et al, 2014; Villeger et al, 2015). In addition to the inverted pendulum model, this suggests that gait can be modelled as a mass on a spring where the ligaments and tendons provide the "springiness" of the movement (ibid). Like the Froude number, the Strouhal number is a dimensionless number, in this case representing the frequency of the gait pattern (Alexander, 1989). However, previous studies including the Strouhal number have focused on linear measures (Delattre et al, 2009; Villeger et al, 2015), and research suggests that fixing stride frequency affects non-linear measures (Terrier and Deriaz, 2013; Terrier, 2019), so we excluded it from this analysis to avoid introducing a confounding variable.

2.3 Data Analysis

Once data was captured, the Vicon software (Vicon Nexus 2.9.1, firmware 7.7) was used to generate joint angle data (Vicon, 2019). Joint angles for sagittal movements of the hip and knee were extracted for analysis, as the other planes of motion have been excluded in previous studies due to increased chance of error (Stergiou et al, 2004a; Georgoulis et al, 2006, Moraiti et al, 2007; Zampeli et al, 2010; Nazary-Moghdam et al, 2019). As these previous studies considered walking, this issue is more relevant for this research as running may increase the error due to soft tissue artefact which is found in particular in abduction/adduction and internal/external rotation (Stagni et al, 2005).

In common with other studies considering non-linear analysis, no smoothing or filtering was done on the data, as this can remove valid points from the analysis by incorrectly identifying them as 'noise' (Myers, 2016). In addition, as the same equipment was used to capture the data for each trial, it can be assumed that the level of noise due to external factors within the sample is consistent, so any changes are due to actual perturbation and variation within the system (Moraiti et al, 2007).

The data collected were analyzed using two non-linear analysis methods, maximum Lyapunov exponent and sample entropy, in order to evaluate both the local dynamic stability of the system and the regular nature of the movement and to evaluate how this varies according to the different speeds tested.

2.3.1 Lyapunov exponents

Lyapunov exponents are used to evaluate the chaotic nature of a dynamical system and measure the rate of divergence of nearby orbits within a phase space (Wurdeman, 2017). Gait data follows a specific path and if we consider the location of a point at t=0 and where this is in relation to nearby paths (the distance between paths is then δ_0) then this same point at time t=τ has a distance of δ_τ from the trajectory, where

$$\delta_\tau = e^{\lambda\tau}\delta_0$$

Equation 3

The parameters used to determine this state space (including the time delay, τ) will be fully discussed later. The Lyapunov exponent is the λ value; a value of zero means that the paths neither converge or diverge and so corresponds to a periodic state, whereas a positive value indicates exponential divergence and that the time series may have a chaotic nature (Wurdeman, 2017). For a time-series of d dimensions, there will be $\lambda_1 \ldots \lambda_d$ Lyapunov exponents. Overall a system may have a combination of zero, positive and negative exponents with a stable system having a negative sum of all exponents (Abarbanel, 1996). Identifying a positive Lyapunov exponent corresponds to randomness or chaos within the time series (Stergiou, 2004a), but calculation of negative exponents has limited value within experimental data (Wolf et al, 1985). Therefore, the maximum Lyapunov exponent (LyE) is used to evaluate the local dynamic stability of the time series, with a positive value indicating a 'strange attractor' (Wurdeman, 2017) or the possible presence of local instability or chaos. This method of assessing local dynamic stability has been shown to be reliable, with running typically resulting in a larger (positive) LyE than walking (Ekizos et al, 2018) suggesting that a running gait is less predictable and stable than a walking gait.

When calculating Lyapunov exponents, the embedding dimension (m) and time delay (τ) parameters are chosen to define the state space of the time series (Wurdeman, 2017). Choosing a time delay that is too small will limit the amount of useful information about how the dynamics of the system change, but too large a value may result in missing data (Stergiou et al, 2004a). The embedding dimension was calculated via the false nearest neighbor algorithm (Stergiou and Decker, 2011) using custom Matlab (R2019a, The Mathworks Inc.) scripts (UNO Biomechanics, 2019). The selection of the appropriate embedding dimension ensures that features of the data are not lost due to assuming a lower dimension than the state space requires, false neighbors in a lower dimension may occur when trajectories appear to overlap, whereas in a higher dimension these are separate (Dingwell at al, 2001). The values for the tolerance for this algorithm were set to the conventional dimensionless ratios,

R_{tol}=15 and A_{tol}=2 (Wurdeman, 2017). The time delay was calculated using an average mutual information algorithm (Stergiou and Decker, 2011) using custom Matlab (R2019a, The Mathworks Inc.) scripts (UNO Biomechanics, 2019). To ensure that the analysis was consistent, both hip and knee angles were analyzed using the values calculated via these algorithms: m=5 and τ=18 data points ($\approx$0.07s in this case). These values are consistent with parameters used in previous non-linear analysis gait studies (Stergiou and Decker, 2011)

A three-dimensional representation of the state space for a single participant is shown in Figure 1 below, but note that the state space is fully represented in >3 dimensions which cannot be demonstrated visually.

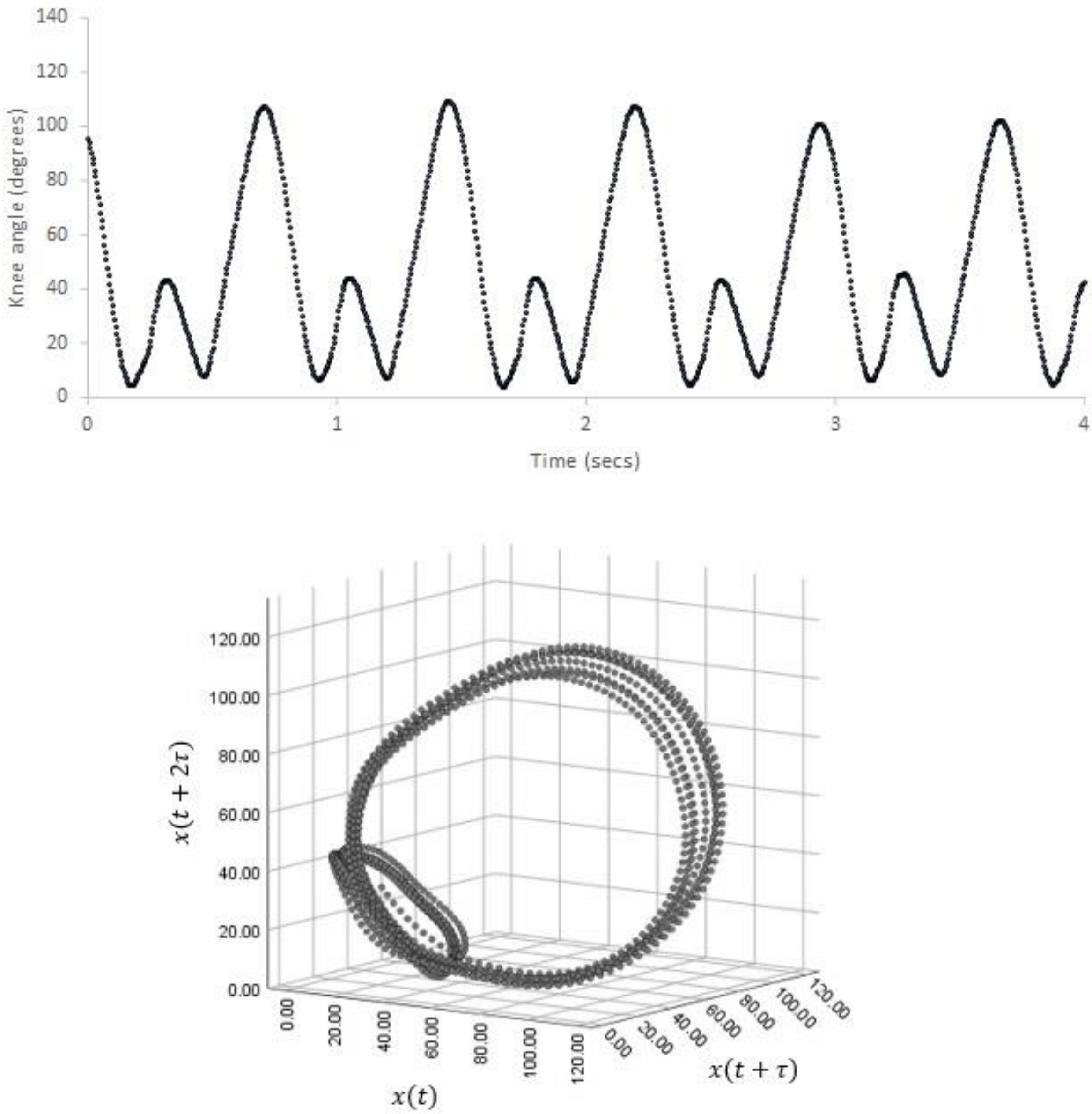

Figure 1: Example sagittal knee angle over time (top) and three-dimensional state space reconstruction of knee angle data (bottom).

The maximum LyE was calculated for each joint angle using a custom implementation (UNO Biomechanics, 2019) of Wolf's algorithm (Wolf et al,1985) which has been shown to be more accurate for small data sets (Cignetti, Decker, and Stergiou, 2012).

2.3.2 Sample entropy

Sample entropy (SaEn) is a measure of the predictability of a time series, with a low entropy value suggesting that the data is predictable and regular (Yentes, 2017). Within gait analysis, a lower entropy value suggests a more regular and repeatable gait. To evaluate sample entropy, a time series is split into a number of vectors, and these are compared to see if they are similar to each other within a certain tolerance level. The size of the vectors, commonly referred to as the window length (Yentes, 2017), is commonly set to 2 for biological systems and the tolerance is conventionally used as 0.2 standard deviations (Stergiou et al, 2004), and these parameters have been used in this research. As each trial captured 2 minutes of running data, this is in excess of the recommended minimum data length of 200 steps and avoids the implicit bias towards regularity in short data sets (Yentes, 2017). The sample entropy was calculated using custom Matlab (R2019a, The Mathworks Inc.) scripts (UNO Biomechanics, 2019).

2.4 Statistical Analysis

The coefficient of variation (CoV) of the group was calculated for each non-linear measure per speed selection method to evaluate the dynamic similarity in each case. A reduced CoV would suggest the speeds for that method produced more dynamically similar movements between participants. To test the significance of the differences in dynamic similarity, a modified signed likelihood ratio test (mSLRT) (Krishnamoorthy and Lee, 2014) was employed, using the R (version 3.6.2) package cvequality (version 0.1.3, Marwick and Krishnamoorthy, 2019). The mSLRT is used to test for equality of coefficients of variance in normal populations. Data was checked for normality using the Shapiro–Wilk test. Standard effect size (ES) calculations are inappropriate or misleading when considering tests such as mSLRT (Johnston et al, 2006) so when results are presented, ES is given as a general measure to quantify the size of the difference between groups.

A one-way ANOVA comparing the non-linear measures at each trial speed ±10% was performed for each of the three trial types (Froude, Fixed, Self-selected) to evaluate whether speed may be a potentially confounding variable when considering gait patterns. This was calculated in SPSS (version 26; IBM SPSS Statistics). Alpha was set to 0.05 for all tests.

3. Results

3.1 Effect of speed

No statistically significant differences were found between speeds ($p>0.05$; $\eta^2< 0.05$), suggesting varying the running speed by ±10% does not affect the local dynamic stability or complexity of the joint motion for a healthy population (see Figure 2). The mean Froude speed was 10.6kmh^{-1} (SD=0.409), which corresponds to the fixed speed, and the mean self-selected speed was 8.2kmh^{-1} (SD=1.757).

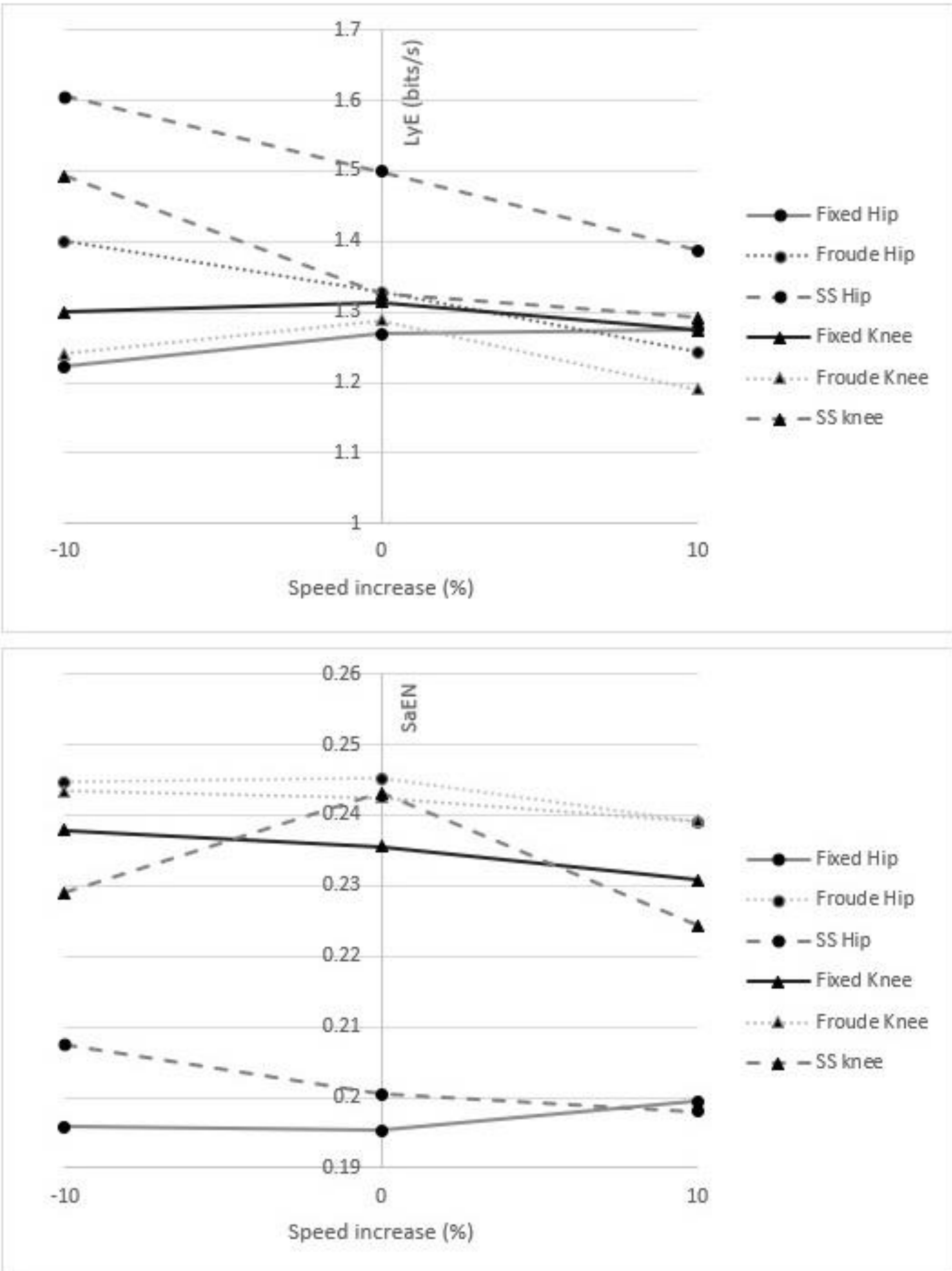

Figure 2: Mean LyE (top) and sample entropy (bottom) for each speed ±10%

3.2 Dynamic similarity

Mean values for all the non-linear measures are similar, with larger observed variability in knee sample entropy when compared to hip sample entropy in particular, as shown in Figure 3.

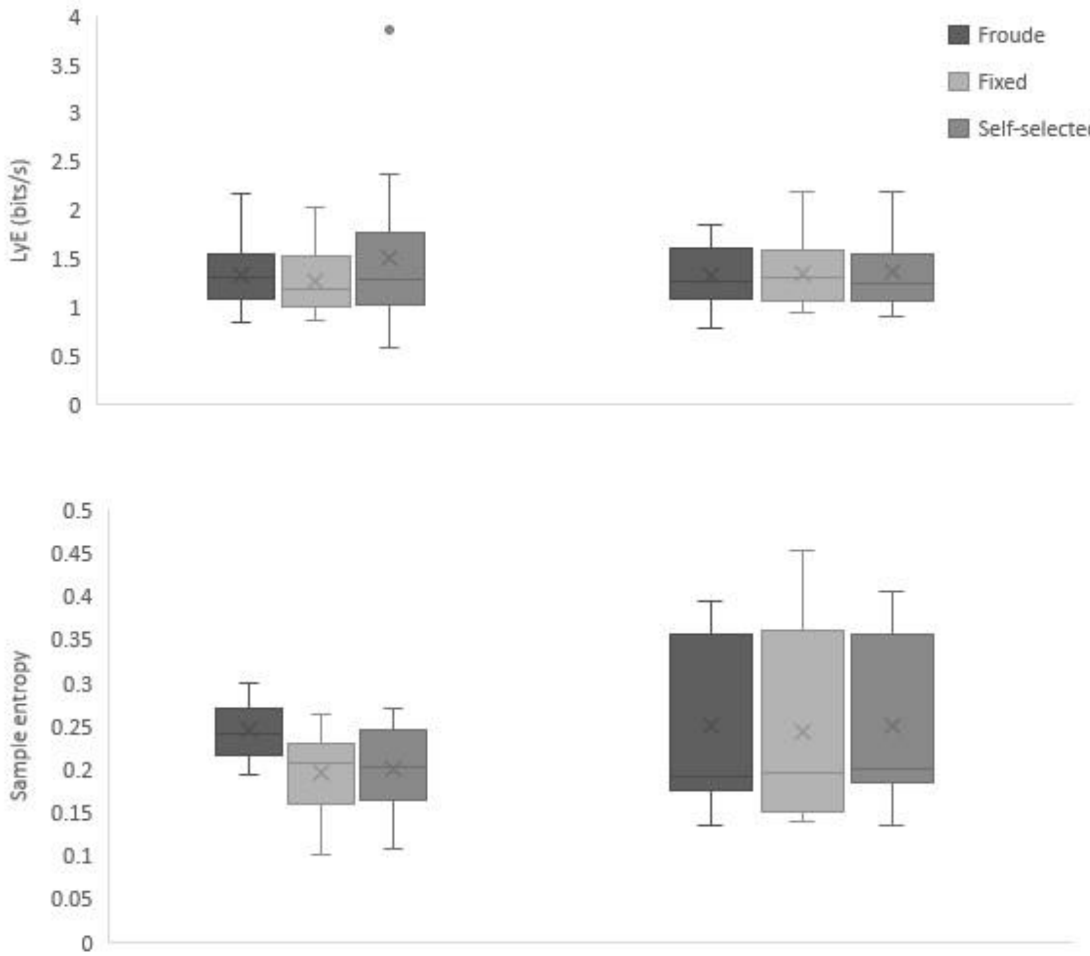

Figure 3: LyE (top) and SaEn (bottom) for hip (left) and knee (right).

The mSLRT found the hip entropy and LyE to have significantly less variation about the mean for scaled speeds compared to fixed or self-selected speed (p = 0.038, ES = 0.142 and p=0.040, ES = 0.254 respectively). However, no significant difference was found in the variations of the knee entropy and LyE between the three speed selection methods.

Additional mSLRTs found that Froude speed had greater dynamic similarity than self-selected speed in hip LyE (p=0.048, ES=0.254), and greater than both fixed and self-selected speed in hip entropy (p=0.015 ES=0.142; p=0.026 ES=0.126).

4. Discussion

The aim of this study was to evaluate the differences between Froude (anatomically scaled), fixed and self-selected speed to establish which produced greater dynamic similarity. Previous studies considering dynamic similarity have compared Froude and fixed speeds, so also comparing self-selected speed has allowed this commonly used protocol to be evaluated, thus informing decisions made in future research.

4.1 Effect of speed

There was no significant difference in non-linear measures of gait variability when changing the speed by ±10% for each speed selection method suggesting that small changes in running speed would not alter the results of analysis, and speed is not a confounding variable when considering an uninjured population. As neither LyE or SaEn were found to be significantly affected by changes in speed for each trial type, this may suggest that participants alter their running gait as the speed changes to maintain an optimal level of stability. Where some studies have found differences in non-linear measures as speed varies these have dealt with an injured population (Georgoulis et al, 2006; Nazary-Moghdam et al, 2019), suggesting that there is a relationship between stability, speed and pathology, rather than purely gait stability and speed. These trials have also considered walking speeds rather than running speeds.

Although the initial pilot testing was based on a sample that was representative of the participant group (for example, biological sex, athletic status, running experience, height, age and weight), the median self-selected speed in the pilot testing group was 22% higher than in the experimental group. This highlights some issues in determining fixed speeds in this manner, but also suggests that the mechanisms behind the choice of self-selected speed are not predictable or reliable, and that using either self-selected speed or fixed speeds based on pilot testing may be inappropriate to reach a consensus across a range of participants.

Participants in this study had a wide range of running experience, with some being complete beginners with no experience of treadmill running. Although each participant had time to familiarize themselves with running on the treadmill, they could still be learning running technique and adjusting their gait pattern accordingly during the trials. It has been suggested that this learning process may cause the participant to increase the regularity and repeatability of their gait pattern to avoid injury and decrease the active number of degrees of freedom (Mitra et al, 1998) which may affect the variability and stability of their gait pattern. Adding an additional constraint of varying speed may further affect this, causing a state of "non-optimal control" (Newell and Vaillancourt, 2001). Further, the duration of each trial could cause individuals to fatigue at different rates, and there may be inter-subject variability as a result of this. However, this research suggests that making small (10%) changes in speed in each trial type is insignificant within the wide range of experience within the group, suggesting that a young and uninjured population adapt quickly to task constraints and adjust their movement variability accordingly to maintain coordination and optimal gait pattern.

4.2 Dynamic similarity

Data analysis suggests that the Froude speed does result in more dynamic similarity between models when considering non-linear measures. Froude speeds can be observed to have less variation in general (see Figure 3) than either fixed or self-selected speeds, this is statistically significant for hip LyE and SaEn. This suggests that using a speed that results in dynamic similarity may remove any issues introduced by lack of standardized protocol in choosing self-selected speeds, as well as providing a scalable, reliable alternative to fixed speeds which do not take anatomical differences between participants into account.

The implication of self-selected and fixed speeds resulting in a greater distribution of variability values is that, at an individual subject level, the differences in speed were influencing the gait variability. This appears to contradict with the findings of the analysis of different speeds discussed above. However, the chosen self-selected speeds differed from the Froude speed by +7% to -45%, which may suggest that speed is confounding at larger changes than ±10%. The choice of self-selected speed may be affected by physiological or psychological considerations, rather than the purely biomechanical considerations which underpin the use of the Froude speed.

Conversely, the fixed speeds were within ±10% of Froude speed, but the hip SaEn for fixed speeds had significantly greater distribution than for Froude speeds. Therefore, the suggestion that larger individual speed changes might have been responsible for the inconsistency between the distribution analysis and the speed analysis, may not hold true here. Fixed speeds applied to a range of participants may cause different reactions due to this being 'unnatural', and this may cause both positive and negative effects to non-linear measures which may not be represented in the average. Scaled speeds should represent an anatomically ideal speed, and so individual reaction to this may be less pronounced. As the distribution of the data was only significantly different for hip SaEn and not LyE, it may well be that this is due to a type I error. Overall, it is unclear what is the mechanism behind this. A significant difference between scaled and other speed selection measures suggests that this is worthy of future consideration, and additional research should investigate this further.

The current study also only found a reduced distribution in the hip variables and not the knee. The hip joint has more potential range of movement than the knee, but the extremes of motion for the knee are very different to the hip when running (Novacheck, 1998) which could suggest that gait perturbations lead to greater potential for corrections at the hip than the knee as speed changes which may support the findings here that the hip is more dynamically similar than the knee movement. Each joint has a different role in stabilizing human gait and studies have suggested that these differences may be due to impact having a larger effect at the ankle, and less at the hip, so the hip may be more sensitive to perturbations than lower leg joints (Son et al, 2009). In addition, while the hip is the main source of power generation, efficient running gait is characterized by minimal pelvic movement (Novacheck, 1998).

Studies considering the use of Froude numbers within walking and running trials using linear measures also found dynamic similarity in each case when compared with fixed speeds (Delattre et al, 2009; Villeger et al, 2014; Villeger et al, 2015). Our research has also evaluated Froude speeds for non-linear measures when running and found this to be less variable, also suggesting that scaled speeds are a legitimate alternative to create similar conditions between participants within non-linear analysis of movement variability. This has also been compared to self-selected speed, and found to provide dynamic similarity in this case too. As running is commonly more prone to changes in local dynamic stability and movement variability than walking (Ekizos et al, 2018), this also suggests that using a scaled speed in walking trials may also provide dynamic similarity within non-linear analysis measures, which future research can evaluate.

Using a speed that aims to create dynamic similarity, such as a Froude speed, may provide a more consistent and easily repeatable methodology than using self-selected speeds, thus improving research quality and accuracy. This also has the advantage of the researcher controlling how close the selected speeds are to walk-run transitions and maximal speeds, which may also affect the movement variability.

4.3 Potential limitations

Despite lacking ecological validity when compared to overground walking or running (Dingwell et al, 2001), treadmills are still used for research as the only way to achieve a consistent, continuous speed. As this study was specifically looking at the effect of changing speed on gait patterns, using a treadmill was considered to be most appropriate, despite not being directly transferrable to overground running. Maintaining a fixed speed during overground running for the length of time required to capture sufficient data for non-linear analysis would be problematic, in addition to increasing the capture volume needed. A large capture volume can affect the quality of the data collected, as a large volume will affect the system resolution, and reduce the precision of the data (Milner, 2008) so using a limited volume by using a treadmill potentially increases data quality and reliably. Further research to address these limitations should be pursued as data capture technology improves and evolves.

5. Conclusion

This study considered fixed, self-selected and scaled (Froude) speeds to evaluate whether dynamic similarity could be achieved when evaluating variability of gait using non-linear analysis. The results suggest that the scaled speed is less variable than either fixed or self-selected. However, this was only for sagittal hip kinematic variability, while knee variability did not differ between speed selection methods.

Small changes in running speed (±10%) did not appreciably affect the local dynamic stability or regularity of the gait pattern in any trial type. This suggests that uninjured young participants adapt to small changes in speed to achieve an optimal level of variability and stability.

This research suggests that the use of an anatomically scaled speed based on anatomical differences between participants is a legitimate consideration for future research, creating similar experimental conditions to increase reliability of results and removing confounding effects due to speed. Future research examining additional joints and planes of movement would explore this concept further, and develop a more rigorous, standardized protocol for human gait analysis research.

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