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A mixed linear modelling characterisation of gender and speed related changes in spatiotemporal and kinematic characteristics of gait across a wide speed range in healthy adults

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ABSTRACT

In exploring the relationship between the kinematics of gait and speed of progression individual variation in patterns and gender differences have not always been adequately taken into account.

In the current study mixed linear modelling was used to isolate changes with speed from those associated with individual variation and gender. Three-dimensional motion analysis of 20 participants (10M/10F, 25.7 ± 5.1 years) walking at a wide range of speeds (normalised speeds 0.10–0.55 ~0.41–2.26 m/s) was recorded (775 walks). Spatiotemporal (speed, cadence, step length, percentage of single and double support) and kinematic characteristics (pelvis through ankle) were determined.

Significant between participant differences were highlighted in both intercept and slope of relationships. In addition females exhibiting different peak pelvic tilt and obliquity, hip flexion and internal rotation and ankle dorsiflexion compared to males. Spatiotemporal parameters exhibited non-linear relationships with normalised speed ($R^2 > 0.5$). Kinematic features exhibited significant relationships with normalised speed, varying from linear to cubic, from very weak to strong in fit ($0.010 > R^2 > 0.672$).

Mixed linear modelling highlighted gender dependent, speed related changes in addition to inter-individual variation. Gender and speed are both important determinants of gait patterns, however, individual variations remain.

1. Introduction

It is well known that changes in walking speed change spatiotemporal characteristics and the joint angles used [1–6]. The exploration of the relationship between characteristics of gait and speed has been accomplished using various methods. For example asking people to walk at ‘slow’, ‘normal’ and ‘fast’ speeds has been used to derive parameters related to a normal speed and a speed lower and higher than this normal speed [2–4,7–9]. This allows the comparison of the outcomes between these groups, providing evidence that there are changes with speed. Alternatively participants in a study have been allowed to walk at their own self-selected speeds and then the speed range covered by the sample has been subdivided into bands of speed and the average results of these bands used to demonstrate speed related changes [10,11]. In other studies the range of speeds has been extended by asking people to walk for multiple walks at a range of speeds both overground [1,5,12–15] and on a treadmill [16–21]. In some of these analyses outcomes have been grouped by speed/speed band and differences used to characterise speed related changes [12,14,15,20,21]. Overcoming the need to use sub-groupings by speed, regression analysis has been presented examining the relationship between speed of walking and gait characteristics [1,5,10,11,16]. Using regression analysis the continuous relationship between an outcome and speed can be assessed. Whilst these methods have provided additional insight into speed related changes these have not necessarily taken gender based differences and individual variation into account. Techniques such as the use of mixed linear modelling can be used to explore the relationship between outcomes and speed whilst factoring in gender differences and allowing for variation between individuals within the analysis [22,23].

Within the current study mixed linear modelling was used to further define the relationship between speed of walking and spatiotemporal and kinematic characteristics for healthy adults while taking into account both gender and individual differences in movement patterns. The hypothesis was that there would be significant speed related changes in gait characteristics and that gender and individual variation would also be important.

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2. Methods

2.1. Participants

Eighteen to sixty year olds (equal numbers of males and females) without lower limb impairment or neurological condition were recruited from staff and students at a UK higher education institution. All participants gave written informed consent based on institutional ethical approval.

2.2. Motion tracking

Three-dimensional motion of participants was tracked using 20 individual markers and 4 clusters (thighs and shanks) of markers attached to the lower limbs (16 camera, 120 Hz) (Qualisys AB, Goteborg, Sweden). This model has been described in detail elsewhere [23]. Segment locations were defined using the markers: pelvis–bilateral posterior and anterior superior iliac spine markers, thigh–hip joint centre and medial and lateral knee markers, shank–knee joint centre and medial and lateral ankle markers, foot–heel and heads of metatarsals 1 and 5 markers. An ordered sequence of rotations (flexion/extension, adduction/abduction, internal/external rotation) was used to calculate joint rotations from the proximal to the distal segment coordinate system.

A static trial was used to define the relationship between the clusters of markers and markers located on anatomical features, allowing the clusters to be used to track dynamic movements. Calculation of all joint angles was accomplished in Visual 3D Professional (C-Motion Inc., MD, USA).

2.3. Data collection protocol

Participants walked along a 6 m carpeted walk way, wearing shorts and bare foot, from a standing start to a designated stopping area. Participants were allowed several walks to become familiar with the set up before data was recorded. For each walk one complete right and left gait cycle were identified over the middle section of the walk way. This maximised the chance of characterising steady state walking by avoiding any speeding up or slowing down at the beginning or end of the walk way.

Participants were required to follow a set protocol in terms of walking speed. First participants walked for three walks at a self-selected normal walking pace. Then participants were asked to walk incrementally slower for a further 7 walks. These started from slightly slower than their self-selected normal walking pace and ended with a walk as slow as they were comfortable walking. Following this participants again walked at their self-selected pace for three walks and then incrementally faster until reaching their fastest walking pace after 7 additional trials. A total of 20 walking trials were therefore undertaken: 6 at self-selected normal walking speed, 7 slower than this and 7 faster than this. The speed of walking adopted covered the entire range of speeds that the participants felt was possible whilst still walking.

2.4. Data analysis

Consecutive left and right strides were identified within the mid-section of the walk way and time points of heel strikes and foot offs determined. Step length was defined as the distance between the heel markers (HEE) at the points of heel strike. Step time was determined as the time between the relevant heel strike time points. Cadence of stepping was defined as 1/step time. Gait speed was defined as the stepping speed, i.e. (step length)/(step time). 100% of the gait cycle was defined as from first to second heel strike on the ipsilateral side. The percentages of the gait cycle in single support, double support and swing were calculated using the relevant heel strike and foot off timings in relation to the gait cycle. Both left and right side outcomes were used within the analysis with appropriate adaptation of outcomes to allow combination of results.

Following methods previously advocated to take into account differences in size of participants, normalisation of data was implemented [24,25]. To achieve this, variables were multiplied by appropriate quantities relating to the size of the participants (Eqs. (1)–(4)):

$$\text{Normalised length} = \text{length} \times (1/\text{Height}); \tag{1}$$

$$\text{Normalised cadence} = \text{cadence} \times (\sqrt{(\text{Height}/g)}; \tag{2}$$

$$\text{Normalised speed} = \text{speed} \times \left(1/\left(\sqrt{(\text{Height} \times g)}\right)\right); \tag{3}$$

$$\text{Normalised time} = \text{time} \times \left(1/\left(\sqrt{(\text{Height}/g)}\right)\right) \tag{4}$$

Where g = acceleration due to gravity = 9.81 m/s^2.

The speed of gait was characterised by the normalised speed of walking.

Changes in outcomes with normalised gait speed were explored using mixed linear modelling. Sequential introduction of terms within the models was used to establish the significance of the contribution of the term to the model. The maximum likelihood was used to estimate coefficients to allow unbiased estimates of −2*logLikelihood (−2LnL). Changes in −2LnL were examined to establish improvements in the model at the level of $p < 0.05$. This required a reduction of 3.84 in −2LnL. Random effects were used at the participant level, allowing differences between participants in intercepts and slopes within the models to be assessed. This allowed unique curves to be generated for each participant, splitting variation between participants at the higher level and speed of progression at the lower level. Gender was introduced as a fixed effect. An unstructured covariance structure was used. Speed, the square of speed and the cube of speed were introduced sequentially and maintained in the model if their introduction improved the model. Random slope by participant was introduced for the highest power of speed as long as a significant improvement in the model was achieved. Once the model had been optimised the restricted maximum likelihood method was used to allow the calculation of unbiased estimates of the model coefficients. To quantify the final model fit R^2 was calculated using the fixed parameters.

The relationships between normalised gait speed and spatiotemporal characteristics of gait including cadence, step length, first double support, single support, second double support and swing percentages of gait were characterised.

Joint kinematics were first examined by graphical presentation of the changes in outcomes across the gait cycle. This was achieved by dividing all results from all participants into 0.05 normalised speed bands from 0.10 to 0.55. From the graphical patterns of the joint angles minima and maxima that followed clear trends with normalised speed were identified. The range of percentage of the gait cycle within which these occurred was defined visually. Each range was selected to allow the identification of the value of the outcome within a particular phase of the gait cycle. Where appropriate both the value and timing of these points was extracted and characterised using the mixed linear modelling method detailed previously.

All analysis was conducted in SPSS v23 (SPSS Inc, Chicago, IL) and used a level of significance of $p < 0.05$. To characterise the level of fit of the final model for each parameter the value of R^2 was evaluated against a pragmatic set of criteria: <0.1 very weak, 0.1–0.3 weak, 0.3–0.5 moderate, 0.5–0.7 strong, >0.7 very strong.