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TauG-guidance of dynamic balance control during gait initiation across adulthood

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ABSTRACT

Measurements from force plates were investigated to identify the life-span developmental course of dynamic balance control during gait initiation across adulthood. Center of pressure (CoP) data of the initial weight shift onto the supporting foot in the mediolateral (CoP_x) direction were tauG analyzed, investigating the hypothesis that tau of the CoP_x motion gap (τ_{CoPx}) is tau-coupled onto an intrinsic tauG-guide (τ_G), by maintaining the relation $\tau_{CoPx} = K\tau_G$, for a constant K. Participants were in their twenties, forties, sixties, and eighties. As regression analysis suggested a strong linear relationship between τ_{CoPx} and τ_G, an investigation of the regression slope as an estimate of the coupling constant K in the tau-coupling equation was justified. Mean K values increased significantly with age from 0.40, 0.47, 0.67, to 0.79, suggesting that control of dynamic balance deteriorates from participants in their twenties making touch contact ($K \leq 0.5$) to participants in their sixties and eighties colliding with the boundaries of the base of support ($K > 0.5$). The findings may prove useful as a measure for testing prospective balance control, a helpful tool for early detection of elderly people at increased risk of falling.

1. Introduction

In almost everything we do, controlling and maintaining balance is of the utmost importance. This is particularly true for successful gait initiation and walking. Humans continuously develop throughout life, and to understand life-span development it is crucial to investigate movement and its underlying mechanisms, and also how these change throughout later parts of life [1,2].

As age increases so too does the fall risk, and elderly individuals are more likely to endure unperturbed falls compared to younger adults. The majority of falls in the elderly happen in transition phases [3]. In particular, initiation of gait requires complex muscular synergies making it the phase where falls are most likely to occur [4]. Even before gait is initiated, postural muscle preparations are made [5].

A recent study [6] detected certain step characteristics of elderly fallers not present in elderly non-fallers or younger adults. The identified pattern of gait initiation in elderly fallers showed a tendency toward shorter first steps as well as a double support period longer than the comparison groups. Others found a decrease in spatial and temporal margins of postural stability as age increased [7]. The spatial margins define the region of stability to the area of center of pressure (CoP) ratio, where CoP is the support of the global ground reaction force on a two-dimensional surface. The temporal margins, on the other hand, define the virtual time-to-collision, which is the approximate time it would take for a collision between the two-dimensional stability boundary and the CoP trajectory to take place [7]. These margins appear to be rather sensitive to aging and they may be of significant importance when it comes to establishing balance stability. Coinciding with these alterations is the reduction in perceptual ability to pick up rapidly incoming information essential to motor control.

The initiation of gait is the intermediary step between bipedal and monopedal stance [3]. Central to gait initiation is the transfer of weight between the two legs as well as maintaining balance during these weight shifts [1,8]. This requires multiple complicated muscle and postural adjustments [9–12] that are known to strain the balance system, offering a particular challenge in elderly individuals [13]. A related issue encountered in the process of balance control during gait initiation is stabilization within the boundaries of the base of support, which entails keeping the vertical projection of the center of pressure within these boundaries [14].

The mathematical function τ_G provides a useful frame for addressing and investigating dynamic balance control during gait initiation. Tau is a theory of sensory guidance of movement [2,14–17]. Central to tau theory are motion gaps. A motion gap is defined as the changing gap between the state the animal is currently in and the goal state it wants to be in which involves the closure of motion gaps. As a motion gap can basically be any

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behavior involving any kind of object or action, motion gaps vary along a number of different dimensions (e.g., length, velocity). However, the underlying factor controlling all possible dimensions has been identified as time [2].

To be able to act upon motion gaps, the time to closure of a gap at its current closure rate, known as tau of the gap, needs to be perceived [16]. Tau of a motion gap equals the size of the motion gap divided by its velocity of change. Tau can be viewed as a primary information variable in regards to movement control [15], and tau-coupling becomes an important notion in this matter. Two taus have to stay in constant proportion over a given period of time to be tau-coupled [2].

Guidance of movement can usually be explained in terms of extrinsic variables and intrinsic variables combined [17]. However, when only one motion gap is encountered and only intrinsic guidance of this gap is available, as when shifting CoP over the standing foot, it is theorized that the nervous system generates a changing canonical energy gap, $G(t)$, which closes in a straightforward Newtonian way, from rest to motion with a constant acceleration [15]. This canonical energy gap is then tied to the single motion gap to achieve tau-coupling. According to tau theory, self-timed and skilled motion gap closures (from rest) follow the τ_G-guidance equation $\tau_{CoPx} = K\tau_G$, where K is a constant during the movement. The value of K in the tau-coupling equation determines relevant kinematics of the movement, and can thus be regarded a scaling factor.

This study investigated, by measuring the abilities of adults in four different age groups, the life-span development of the control of the movement of CoP as it shifts over to the supporting foot during gait initiation. It was expected that with age, control of the movement of CoP would deteriorate. It was postulated that controlling CoP movement in the mediolateral direction (CoP_x) entails controlling the closure of the motion gap between the current position of the CoP_x and a goal position lying within an upright imaginary cylinder that surrounds us when we walk; and that this is achieved by tauG-guiding the motion gap, i.e., keeping the changing tau of the motion gap proportional to an intrinsically generated changing tau value, τ_G. It was expected that the eldest participants would overshoot the goal position (rather than making touch contact with it, as the younger participants would), because their τ_G-guidance of CoP_x has started to deteriorate.

2. Methods

2.1. Participants

A total of 28 participants volunteered to take part in the study. Participants were equally divided into four age groups where the youngest participants (group 1) were between 23 and 29 years (3 males, 4 females), mean age 25.8 years. The middle age groups (groups 2 and 3) were between 40 and 48 years (3 males, 4 females), mean age 43.4 years and between 60 and 69 years (4 males, 3 females), mean age 65.8 years. The oldest participants (group 4) were between 80 and 90 years (4 males, 3 females), mean age 82.8 years.

The youngest participants were students from master level classes in psychology, participants in group 2 were recruited among employees at the Department and acquaintances, while participants in the two oldest age groups were recruited from the senior division of Trondheim's Gymnastics Club.

None of the participants had a history of fall accidents or problems related to motor and/or balance control. In the oldest age group, three participants reported using sleep medication on a frequent basis. All participants reported normal, or corrected to normal vision. Seven participants reported not exercising on a regular basis (one in group 1, three in group 2, one in group 3, and two in group 4), while the remaining 21 participants reported doing cardiovascular and/or weight training sessions at least once a week. All participants gave their informed written consent upon participation in the study.

2.2. Apparatus and procedure

Custom built force plates were used for sampling center of pressure data. Four plates (92 × 83 cm each) were lined up so as to form a continuous walkway. The two plates in the middle were used for data collection. Sampling rate was 100 Hz, and all trials were recorded on video.

A trial would employ the following procedure: participants stood still for 3 s and upon signal from the researcher walked across the platform. All participants were instructed to walk normally and with good pace, and they were allowed to start with their preferred foot. All participants wore shoes during testing, and they completed 12 trials each.

2.3. Data analysis

Control of movement of CoP_x was analyzed during gait initiation. The raw data files were Gaussian filtered with a sigma of 3 (30 ms). Velocity and displacement of CoP_x were plotted against time, and the beginning and end of the CoP_x gap closure was identified as the times where CoP_x was equal to 10% of peak velocity. The function $\tau_G(t)$, the τ of the gap, $G(t)$, is derived from Newton's equations of motion as $\tau_G(t) = (1/2)(t - T_G{}^2/t)$, where time, t, runs from zero to T_G, the duration of closure of the gap, G(t), and was employed for calculating and plotting τ_{CoPx} against the tauG-guide (τ_G) for the movement [15]. The hypothesis predicts that skilled, self-timed closure from rest of our motion gap, CoP_x, will follow the tauG-guidance equation, $\tau_{CoPx} = K\tau_G$, where K is a constant during the movement.

Fig. 1 uses real data to demonstrate the tauG analysis procedure. In Fig. 1a displacement of CoP_x and its corresponding velocity are plotted against time, and the vertical lines mark the start and end of the motion gap. In Fig. 1b, τ_{CoPx} and τ_G are plotted against time to illustrate the co-variation between these. Finally, in Fig. 1c a linear regression analysis was run between the two taus to determine the coupling strength between τ_G and τ_{CoPx} (as measured by the value of the regression coefficient, r^2), as well as estimate the value of the constant K in the tau-coupling equation $\tau_{CoPx} = K\tau_G$ [14], as measured by the regression slope.

Thus, for each trial two values were given: (1) the value of r^2, and (2) the regression slope serving as an estimate of the value K in the tau-coupling equation. If the r^2 values are high, this will allow the regression slope to be a valid estimator of the K of the movement.

K is the parameter in the tau-coupling equation which regulates the kinematics of closure of the gap [17]. Hence the K value reflects the degree of control during a gap closure, in the present study identified as the first weight shift over the supporting foot during gait initiation. K has three ranges, where each defines a particular kind of movement. When $0 < K \leq 0.5$, the movement is controlled and ends with touch contact with the boundaries of the base of support. When $0.5 < K < 1$, the movement is less controlled and ends with hard contact with the boundaries of the base of support. Such a movement is characterized by a steeper decrease in closure rate, and an asymmetrical acceleration/deceleration phase, where the latter is shorter than the first [14,17]. When $K \geq 1$, the movement is characterized by a lack of a deceleration phase hence the movement only accelerates, also upon reaching its goal, and the movement results in a non-controlled collision with the boundaries of the base of support [2].

3. Results

3.1. τ_G-guidance analysis

A total of 336 trials were recorded and used for analysis. In all trials r^2 values were very high, giving the following group mean r^2 values for participants in their twenties: 0.989, forties: 0.993, sixties: 0.995, and eighties: 0.986, indicating that the tau of CoP_x was strongly coupled onto the tauG-guide. Therefore, further analysis was performed on the K values, which show how well the movement of CoP_x was controlled.

Group mean values for K were as follows for participants in their twenties: 0.40 (range 0.37–0.53), forties: 0.47 (range 0.38–0.55), sixties: 0.67 (range 0.45–0.78) and eighties: 0.79 (range 0.67–0.87). A one-way ANOVA examining participants' K values was conducted with groups as a between factor. This revealed a main effect of age, $F(3,24) = 34.07$, $p < 0.001$, indicating progressively higher K values, and thus poorer control, as age increases.

Participants' mean K values were tested with a one-sample t-test to examine whether the results were significantly higher or lower than 0.5 (see Fig. 2). Participants in their sixties and eighties had mean K values significantly higher than 0.5 with $t(6) = 4.00$, $p < 0.01$ and $t(6) = 8.76$, $p < 0.001$, respectively, indicating that they collided with the boundaries of the base of support during the preparatory CoP_x shift before executing the first step ($K > 0.5$). Characteristics of participants in their sixties and eighties were K values well above 0.5, with $K \leq 0.5$ in only 16% and 7% of the trials, respectively. The participants in their twenties retrieved mean K values significantly lower than 0.5, $t(6) = -4.54$, $p < 0.01$, indicating that they made