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Perceptual-Motor Regulation in Locomotor Pointing while Approaching a Curb

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Highlights

- Locomotor pointing was assessed in an everyday task; approaching to step up a curb.
- In approaching the curb, step length was regulated by perceptual-motor coupling.
- Locomotion was generally aimed at positioning on a curb, rather than before it.
- Approaching a curb provides a measure for assessing perceptual-motor control.

Abstract

Locomotor pointing is a task that has been the focus of research in the context of sport (e.g. long jumping and cricket) as well as normal walking. Collectively, these studies have produced a broad understanding of locomotor pointing, but generalizability has been limited to laboratory type tasks and/or tasks with high spatial demands. The current study aimed to generalize previous findings in locomotor pointing to the common daily task of approaching and stepping on to a curb.

Sixteen people completed 33 repetitions of a task that required them to walk up to and step onto a curb. Information about their foot placement was collected using a combination of measures derived from a pressure-sensitive walkway and video data. Variables related to perceptual-motor regulation were analysed on an inter-trial, intra-step and inter-step level.

Similar to previous studies, analysis of the foot placements showed that, variability in foot placement decreased as the participants drew closer to the curb. Regulation seemed to be initiated earlier in this study compared to previous studies, as shown by a decreasing variability in foot placement as early as eight steps before reaching the curb. Furthermore, it was shown that when walking up to the curb, most people regulated their walk in a way so as to achieve minimal variability in the foot placement on top of the curb, rather than a placement in front of the curb. Combined, these results showed a strong perceptual-motor coupling in the task of approaching and stepping up a curb, rendering this task a suitable test for perceptual-motor regulation in walking.

Keywords: motor control, locomotor pointing, perceptual-motor regulation, locomotor approach

Introduction

Placing one's foot onto a target on the ground during gait, otherwise known as 'locomotor pointing', is important in athletic contexts (e.g. the run up for a long jump) as well as everyday walking. Appropriate locomotor pointing in sport is often critical (e.g. every centimeter of error in the long jump run-up is a centimeter lost in the jump) and this has led to extensive study in the sporting context [1–10] and research on perceptual-motor regulation strategies in locomotor pointing [2,11,12]. With the aim to devise a suitable task for perceptual-motor regulation in walking, the current study investigated whether these results generalize to the everyday task of approaching and stepping up on to a curb.

Early studies on locomotor pointing were performed in the run up for a long jump [1–8]. In this event, it is important for an athlete to regulate their running gait in such a way so as to ensure that they end their run-up with their take-off foot as close to the edge of the take-off board as possible. It was shown that this low error is achieved through visual regulation [1,2]. In the initial stage of the run up, foot placements are more variable, but become more consistent later in the performance when the athlete enters a regulation phase to ensure that they end with minimal error between the positioning of their foot and the edge of the take-off board.

Two previous studies of locomotor pointing have sought to determine when visual regulation was *initiated*, by examining locomotor pointing on a trial-by-trial basis. One study focused on the long jump run up [2] and the other study focused on a walking task that involved participants stepping over an obstacle [13]. Both these studies defined the onset of regulation as the moment that steps in the run-up or walk became different from the average step length recorded under steady-state conditions. Results indicated that the onset of regulation was not fixed, but rather, was related to the amount of adjustment required. They showed that if greater adjustment was required, the onset of regulation was earlier compared to runs or walks with lower required adjustment. Ultimately, these results indicated that the onset of regulation was dependent on continuous perception-movement coupling [2,13].

Locomotor pointing is a skill that is often executed in daily life and is important during tasks such as approaching a set of stairs or a curb. Despite this, research has mainly focused on tasks that are not commonplace in daily life, such as sporting tasks [1–10] as well as laboratory tasks such as stepping onto or over abstract targets. For some of these studies, the target has only appeared moments before the required step (e.g. [14]) or has been incorporated into specific laboratory equipment, such as treadmills [15] or virtual reality systems [12]. By incorporating a task that involves an every-day activity, the current study aimed to generalize the findings of previous locomotor pointing research [2,13] to everyday situations. Whilst the current study is still laboratory-based, the required action more closely approximates and, hence is more generalizable to every-day behaviors than any of the preceding studies.

The task used in the current study involved stepping onto a regulation-height - *curb-like* – two meter long platform. Stepping up onto such a curb-like platform is different from stepping on a target or avoiding obstacles in the sense that the spatial demands are lower as a curb does not dictate where and how to step up. A step up can be achieved via any place in front of the curb, to any place on top, as long as the demands of the step stay within a person's action capabilities. These lower accuracy demands allow a step up that would not require a large decrease in walking speed [16]. These demands are not as strict as, for instance, those of a long jump, in which locomotor speed requirements are high and each centimeter away from the take-off board means a centimeter shorter jump distance. Compare this to the approach to a curb in which a foot positioned too close to the curb will turn the curb into a tripping hazard and a position too far away will make the curb unreachable. Both of these scenarios have negative consequences for the efficiency of progression.

The current study aimed to investigate whether previous results in locomotor pointing regulation in a setting with higher spatial demands (the long jump approach [2], walking to specific targets [13]) can be generalized to approaching a curb. As age-related declines in cognition and action capabilities make it unethical to evaluate perceptual-motor regulation during high-speed movements, such as the long-jump approach, this study has the potential to provide new opportunities to study this process in an ageing population. However, before being able to use the curb-approaching task as a measurement tool for perceptual-motor regulation, the current study compared regulation in this task to the previous studies of locomotor pointing. Specifically, we aimed to assess whether, similarly to other studies of perceptual-motor regulation [2,13], a decrease in variability of step placement is shown when an individual approaches a curb-like platform and whether this regulation is dependent on the required adjustment (implying a continuous coupling between perception and action).

Method

Participants. Sixteen healthy participants (9 males, 7 females) volunteered to participate in the study (mean (SD) age: 25.5 (3.8) years). All participants were recruited from the university environment, had normal or corrected to normal vision and signed a consent form prior to their participation. The protocol of the study was approved by the institutional Human Research Ethics Committee.

Protocol and Materials. Participants were instructed to walk 8.5-meters along a pressure-sensitive walkway (GAITRite®, CIR Systems, Inc., Franklyn, NJ, USA), starting from a constant starting position at one end of the GAITRite mat and before stepping onto a purpose-built curb-like platform (dimensions LxWxH: 2.00x1.00x0.15 m) positioned at the other end of the walkway (creating a 10-m walk). A switch was fitted to a post (height 1.35 m) at the far end of the platform and participants were instructed to "walk up to the platform, step up and flick the switch at the far end" to signal the end of each trial. Prior to data collection, participants performed a minimum of three practice walks along the walkway and onto the platform to establish their preferred step length, which was used to set up the main experiment. If the experimenter judged one of the three practice walks to be inconsistent in terms of step length (for instance, some participants started their first walk more cautiously), the data from this trial was excluded and an extra walk was performed to ensure a representative average.

The aim of this experiment was to assess similarities between a long jump running approach [2,13] and a walking task, but the dimensions of our lab did not allow our participants enough space to complete a similar number of strides to that which would be used in a long jump approach. Given that research has shown that variability in foot placement accumulates during the initial phase of the long jumping approach [1], athletes are inevitably exposed to different task demands each time they enter a regulation phase and variability is minimized. Similarly, when approaching a curb in the real world environment, the conditions that an individual performs under, such as their starting position relative to the curb, are rarely identical over repeated performances. As such, the current study used the following manipulation to promote variability in the demands of each repeat performance and to better replicate the circumstances experienced in real life when entering the regulation phase. Participants were instructed to place one of their first steps on a target mat of anti-slip material (bright blue color, dimensions LxW: 0.30x1.50 m) that was positioned in one of 10 different positions in front of the participant's starting position at evenly spaced distances ranging from 1 to 2.5 times their preferred step length. Participants were asked to place their full foot on the anti-slip material, but were not limited with respect to the number of steps that they took to achieve this goal (i.e. some may have taken one step, while others would have taken two or three steps). Participants were asked to try and incorporate stepping on the target in their natural gait and to continue walking along the walkway as naturally as possible. The target mat at the start of the walkway was presented as a secondary goal; their primary goal was reaching the switch at the end of the walkway. If a participant was unsuccessful in placing the full foot on the target at the start of the walkway, the trial continued as normal, with the participant walking further towards the platform (no outcomes were derived from this procedure). An 11th condition was added in which no target was presented and the participant walked freely towards the platform. Conditions were repeated three times each and were presented in a random order, resulting in a total of 33 trials per participant.

Information about the participants' foot placements was automatically collected and digitized by the GAITRite system; the forefoot centroid computed by GAITRite was extracted and used to represent the foot position relative to the curb. This foot placement data was exported to Microsoft Excel. As the GAITRite system was incapable of measuring foot positions on top of the platform, information about foot placements immediately prior to and on the platform was also captured using a digital video camera (CASIO, EX-FH100) positioned 2.35m from the edge of the platform, perpendicular to the direction of walking. Calibration of the video footage was completed using two reference markers placed 30 cm apart on the closest side of the platform. Videos were analyzed using Kinovea (version 0.8.15, ©2006-2011 Joan Charmant & Contrib.) by three research assistants, in order to extract the position of the forefoot from the participants on top of the platform. Videos from three participants (396 foot placements identified by each assessor; 3 participants * 33 walks * 2 footfalls * 2 coordinates: heel and toe measures) were rated by all three assistants. Inter-rater reliability was determined to be excellent (ICC=0.99).

To validate the measures derived from the video camera, the footfall data for four participants were collected using a Vicon 3-dimensional motion analysis system (Vicon Motion Systems), with a marker positioned on the shoe of the participant approximately on the distal end of the second metatarsal. Bland-Altman plots (Appendix 1) illustrated that the error between the GAITRite and Vicon systems (0.09 cm average) and the video- and Vicon-based measures (0.88 cm before step up and 0.09 cm after) was very low.

Dependent variables. Using MATLAB (version R2015a, © 1984-2015 The MathWorks, Inc.) a series of dependent variables were derived from the foot placement data [2,13]. Specifically, *inter-trial, inter-step* and *intra-step analyses* were performed.

For the *inter-trial analysis*, the standard deviations around the average position of the foot for each footfall relative to the curb ($SD_{footfall}$) were calculated for each participant across the 33 trials. Specifically, the average placement of the foot for the first step onto the curb was denoted as footfall0, while the average placements of the foot for the preceding steps were labeled relative to footfall0 (footfall-1, footfall-2… footfall-n; see Figure 1). Following previous studies [2,8,13] the onset of regulation - the average moment at which a participant initiated regulation - was established as the step at which $SD_{footfall}$ started to decrease, without showing an increase at one of the later steps.

INSERT FIGURE 1 ABOUT HERE

Further analysis compared the variability of foot placements right before and after stepping up the curb for each participant. The assessment of whether the minimal variability was found at the former or the later foot placement indicated whether a participant aimed gait towards a constant location before the step up, or a constant position on the pavement.

For the *inter-step analysis,* each walk was analyzed individually. A 'standard step length' (SSL) was derived as the mean of the step lengths of the early, steady state steps (step 5-8 counting back from the step onto the platform, similar to [13]). Then, all later steps were compared to this SSL. Steps that were more than 2 SD's larger than the SSL were marked as lengthening steps, whilst those that were more than 2 SD's smaller were marked as shortening steps [13]. A trial was considered to be regulated when at least one of its individual steps was marked as either lengthening or shortening. The regulated trials were categorized as; i) lengthening trials when only lengthening steps were used; ii) shortening trials when only shortening steps were used; and iii) mixed trials when a combination of step adjustments was used. The total amount of adjustment per trial (S_{trial}) was using Equation 1.

$$S_{trial} = \sum |SL_i \ - SSL| \qquad \text{Equation 1.}$$

In which SL is the step length with i denoting the step number as in Figure 1, SSL represents the standard step length for a given trial. This 'sum of adjustment' per trial was compared to the step number of the first regulated step per trial to assess the relationship between the amount of required adjustment and the onset of regulation.

For the *intra-step analysis,* a standard foot position pattern was calculated per participant, as the mean footfall position for each footfall over all trials (FootFall mean: FFm_i, with i denoting the footfall number as in Figure 1). Also, a standard step length pattern was derived as the mean step length per step number for the 33 trials (Step Length mean: SLm_i). Equation 2. represents the adjustment required ($A_{required}$) per footfall (FF_i), with i denoting the footfall number (Figure 1).

$$A_{required} = FF_i - FFm_i \qquad \text{Equation 2.}$$

This variable was named 'adjustment required' as it represents the error between the current location and the average for that footfall. Similarly, 'adjustment produced' ($A_{produced}$) was computed by using Equation 3 for each step length (SL), with i denoting the step number (Figure 1).

$$A_{produced} = SL_i - SLm_i \qquad \text{Equation 3.}$$

These values were entered in a linear regression to assess the relationship between the adjustment required in any footfall and the adjustment produced in the following step for all participants (Figure 1). Alpha was set to 0.01 for both the *inter-step* and *intra-step analyses* [13].

Results

To allow comparison with previous studies, it was important that our different conditions successfully induced variability in the walking patterns of the participants. Averaged over all participants, six steps before stepping up, $SD_{footfall}$ was 24.95 cm. This is similar to values reported by the previous study of Cornus et al. [13], who use a gymnastics run up track of 25 meters to induce variability in foot placement.

INSERT TABLE 1 ABOUT HERE

Table 1 shows the descriptive information of our participants. There was low variability in step length, cadence and velocity, confirming that there was relative homogeneity in terms of the action capabilities of the participants. Approaching the curb, variability in foot placement decreased (Figure 2A and 2B), whereas on average, a lengthening of steps was observed in the final two steps (Figure 2C and 2D). The onset of regulation was variable between participants and spread between eight and four steps before the step up (Table 1). Only one participant showed a minimal $SD_{footfall}$ at the last step before stepping up (red data in Figures 2B and 2D), all others had a minimal $SD_{footfall}$ on the platform (blue data in Figures 2B and 2D).

INSERT FIGURE 2 ABOUT HERE

Inter-step analysis. The inter-step analysis identified 87% of the trials to be categorized as 'regulated' (over all participants: 460 of 528 trials, range: 73%-100%). In total, 134 trials were classified as lengthening, 221 as shortenings and the remaining 105 were categorized as mixed. Linear regression analyses highlighted significant relationships between the sum of adjustments per trial (a summation of the differences between each step and a standard step in that trial) and the timing of the onset of regulation (Figure 3). These relations show that participants initiated regulation earlier in trials that required more adjustment; indicating that the onset of regulation was related to the perception of the adjustment required. Specifically, significant linear relationships were identified for the shortening trials ($Y = -2.63x + 6.06$, in which Y is the total amount of adjustment in the trial and x is the step of regulation onset; $R^2 = 0.10$; $p = 0.001$) and the lengthening trials ($Y = -4.69x + 10.63$; $R^2 = 0.23$; $p < 0.001$), but not the mixed trials ($Y = -1.11x + 12.91$; $R^2 = 0.01$; $p = 0.344$).

INSERT FIGURE 3 ABOUT HERE

Intra-step analysis. The regression analysis found a significant linear relationship between the amount of adjustment required at a certain footfall and the amount of adjustment produced in the following step (Figure 4). This relationship was significant for all steps starting 6 steps away from the platform ($Y = 0.02x - 0.01$, in which x is the required adjustment and Y is adjustment produced; $R^2 = 0.05$; $p < 0.001$) and remained linear with increasing steepness (beta increases from 0.02 at $step_{-6}$ to 0.29 at the $step_0$) and increasing R^2 values towards the last footfall ($R^2 = 0.05$ at $step_{-6}$ and increases to $R^2 = 0.69$ at $step_{-1}$). Interestingly, at the step onto the curb ($step_0$), the R^2 value was lower than at the previous step (R^2 at $step_0 = 0.44$).

INSERT FIGURE 4 ABOUT HERE

Discussion

The main aim of this study was to assess whether perceptual-motor regulation is evident in the task of approaching and stepping onto a curb-like platform. Overall, the results indicated that a similar type of perceptual-motor regulation is apparent as what has previously been reported in the run-up for long jumping [1,2,5] and the approach to step over an obstacle [13].

The results from the inter-trial analysis showed that variability of foot placements decreased when participants drew closer to the curb, similar to previous findings in other locomotor pointing tasks. In a previous study on stepping over obstacles, the standard deviation of footfall position decreased to only 0.05 m [13]. Our results were less pronounced. The average minimal variability of the standard deviation of footfall position in the current study was 0.12 m. Our participants initiated regulation earlier. Variability started to decrease as early as eight steps before the minimal variability occurred, whereas five steps before an obstacle was the earliest found in previous research [13].

The finding that regulation of step length variability when approaching a curb was similar compared to that previously reported in studies concerning the long jump approach is interesting and indicates that the task of approaching a curb could be used to measure perceptual-motor regulation. This is particularly relevant since a recent review [17] showed that research into perceptual-motor research is often performed on convenience samples comprising younger adults and not, for instance, in aging or clinical groups. Long jumping as a task to measure perceptual-motor control would be impractical (if not unethical) for these cohorts, but approaching and stepping up a curb could be a representative alternative, to enable measurement of perceptual-motor coupling and the development of diagnostic instruments for atypical perceptual-motor coupling.

Most participants (15 out of 16) regulated their gait to aim for a placement on the platform, as shown by minimal variability being recorded at their footfall on top of the platform. It is interesting to think about why one strategy would be picked over the other. It could be hypothesized that this relates to certain strategies of approaching. Aiming for a standard placement in front of the step up might be reflective of a more cautious strategy; a person can position him or herself in the best location to enable a safe step up. In contrast, other participants might aim for the curb to prioritize smooth progression. The current study found that, in general, our participants lengthened their steps when approaching the platform. This is unsurprising as research has shown that participants prefer to lengthen their steps instead of shortening when confronted with an obstacle [18]. This also might be the result of a trade-off between the safety of a more cautious walk with smaller shortened steps versus an adjustment using larger lengthened steps with greater efficiency [19]. Following this reasoning, it will be interesting to replicate these results using participants that might be more tempted to make cautious decisions, such as older adults. With older age, people are known to walk more cautiously, in order to cope with their decreased gait and balance capabilities. Furthermore, despite local government regulations, curbs in various cities and countries around the world are unlikely to be exactly the same height. As a higher curb would be more demanding than a lower curb, individuals may exhibit different perceptual-motor regulation when approaching these different obstacles. Future research is required to better understand the influence of such changes on the relationships between a person, their environment (the curb) and their perceptual-motor regulation.

The results of the regression analyses in the inter-step analysis showed that the moment at which participants altered their gait patterns was related to the total amount of adjustment required for the shortening and lengthening trials, but not for mixed trials. These results replicated those of previous studies that involved stepping over obstacles, which also reported the relationships to be significant for lengthening and shortening trials, but not mixed trials [13].

The results from the intra-step analysis indicated that the adjustment produced in each step was related to the required adjustment in the previous foot placement as early as six steps before step up. Similar relationships have been identified in previous research, though generally they show the relationship to reach significance later in the task; namely three [12,13] or four steps [2] before the target. Compared with the walking to step over a target task of Cornus et al. [13], which reported that the relationship between required- and produced adjustment became stronger throughout the task, our results were similar in the approach phase, with a slightly weaker relationship for the final step onto the curb.

It is relevant to note that all of our analyses showed that our participants started their adjustments earlier than indicated by previous studies. It has been reported that with higher spatial demands, regulation was initiated earlier [13]. The spatial demands associated with our tasks could be considered lower than the demands associated with the experimental tasks used in previous studies, in which participants were free to choose where to place their feet. A possible explanation for this finding is that participants were very familiar with our task. Past experiences in stepping up curbs could have made them more attuned to relevant visual information, making them recognize important constraints sooner and enabling regulation earlier, compared to the approach participants were required to make to abstract obstacles in previous study [13]. Another explanation could be the presence of the flick button at the end of the platform. Studies in the run-up of cricket bowlers have shown that having a vertical reference point (such as the umpire in cricket or the vertical post with the button in the current study) makes participants regulate earlier in their run [10,20]. Furthermore, it has been shown that a nested task (such as assuming an appropriate posture) could influence regulation even further [20]. Our task of flicking a button at the end might have had a similar influence in locomotor pointing towards the platform. Future research should seek to study these effects further and to examine the influence of performing similar tasks in truly natural settings, such as outdoors.

In conclusion, the current study showed that the regulation that has previously been described for locomotor pointing in the long-jump run up [2,11] and stepping over an obstacle [13] is also present when stepping onto a curb. Overall, our analyses showed that participants initiated regulation earlier than shown in previous research and suggests that young people typically aim for a specific position on the curb rather than for a specific placement in front of the curb. The finding that perceptual-motor regulation can be measured in this type of locomotor pointing is an important one. The task described in this paper can now confidently be used as a measure of perceptual-motor regulation in locomotion that has low demands and can be used in any target population. This introduces potential measures for use with older adults and clinical groups, whose frailty might prevent them from being tested with more demanding tasks. Studying perceptual-motor regulation in older cohorts will be an interesting topic of future research as it is currently unknown how age-related declines in action capabilities affect perceptual-motor coupling.

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Appendix 1. Bland-Altman plots for validation of video data

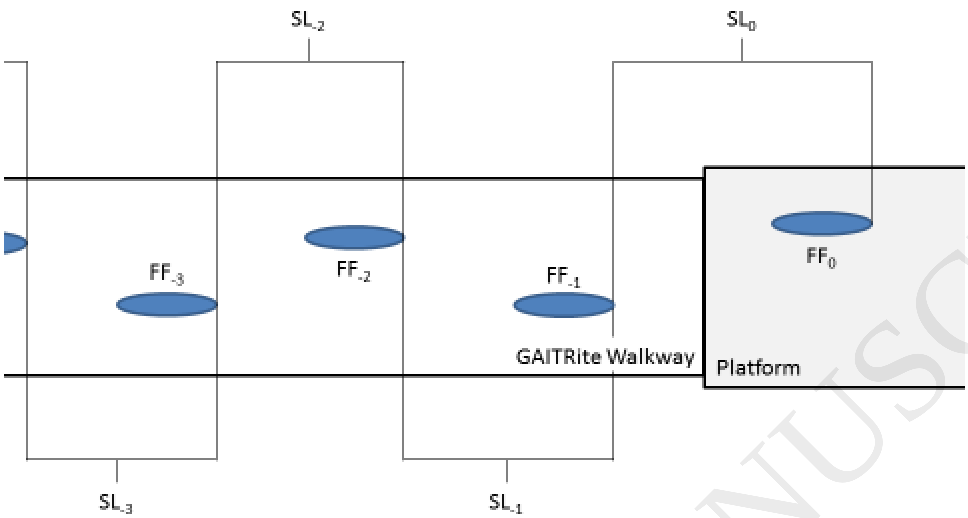
INSERT SUPLEMENTARY FIGURE 1 ABOUT HERE

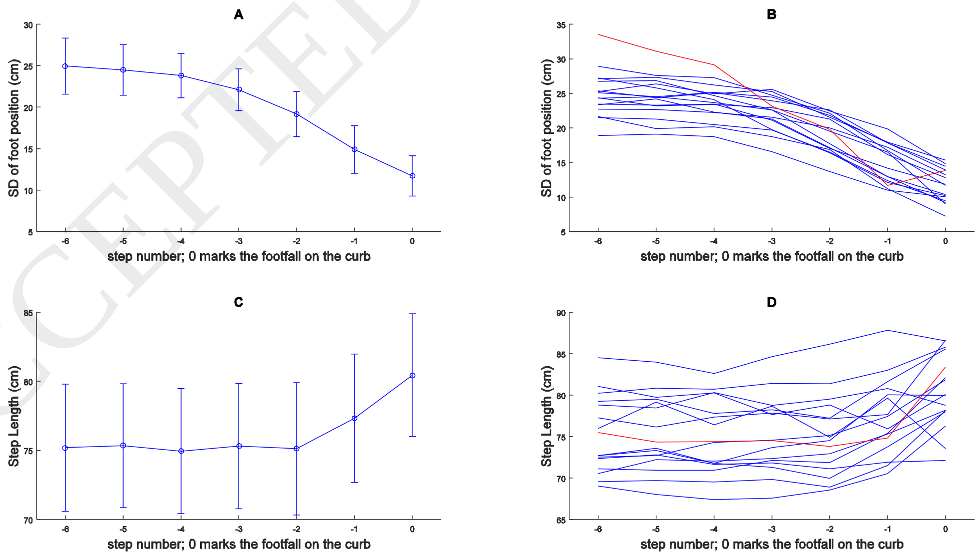
Figure 1. A coding example for the walk up to the curb. The first footfall on the platform is coded as FootFall (FF) $_0$ and all other footfall placements are coded in relation to FF_0. The step length onto the platform is coded Step Length (SL) $_0$ and all other step lengths are coded in relation to that step.

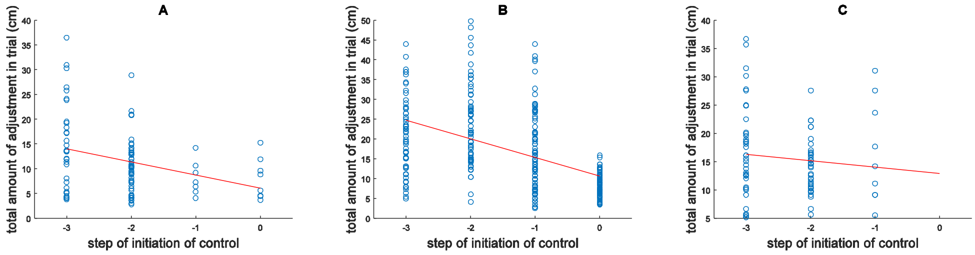
Figure 2. Data is represented per footfall leading up to the curb, with 0 being the first footfall on the platform. Panel A shows the mean ± 1SD of toe-curb distance in centimeters for all participants (N=16) over 33 walks. Panel B shows individual data, with standard deviation of footfall position over 33 walks. Panel C shows the mean ± 1SD of step length, for all participants, whereas panel D shows individual data of step length, providing insight into the nature of step adjustments. Blue data represents participants with a minimal SD for the footfall on top of the platform and red data represents the one participant with a minimal SD at step-1.

Figure 3. The relationship between the total adjustment shown in a walk and initiation of regulation for shortening trials (A; N = 221), lengthening trials (B; N = 134) and mixed trials (C; N = 105). A significant linear relationship is evident for shortening (p=0.001) and lengthening (p<0.001), showing that the onset of these types of regulation is dependent on the required amount of adjustment.

Figure 4. Linear regression analyses per step number for the required adjustment (Pi-Pmi) and the adjustment produced (Li^{-1}-Lmi^{-1}). The relationship is statistically significant at all measured steps (up to step -6).






A
B
C
total amount of adjustment in trial (cm)
step of initiation of control

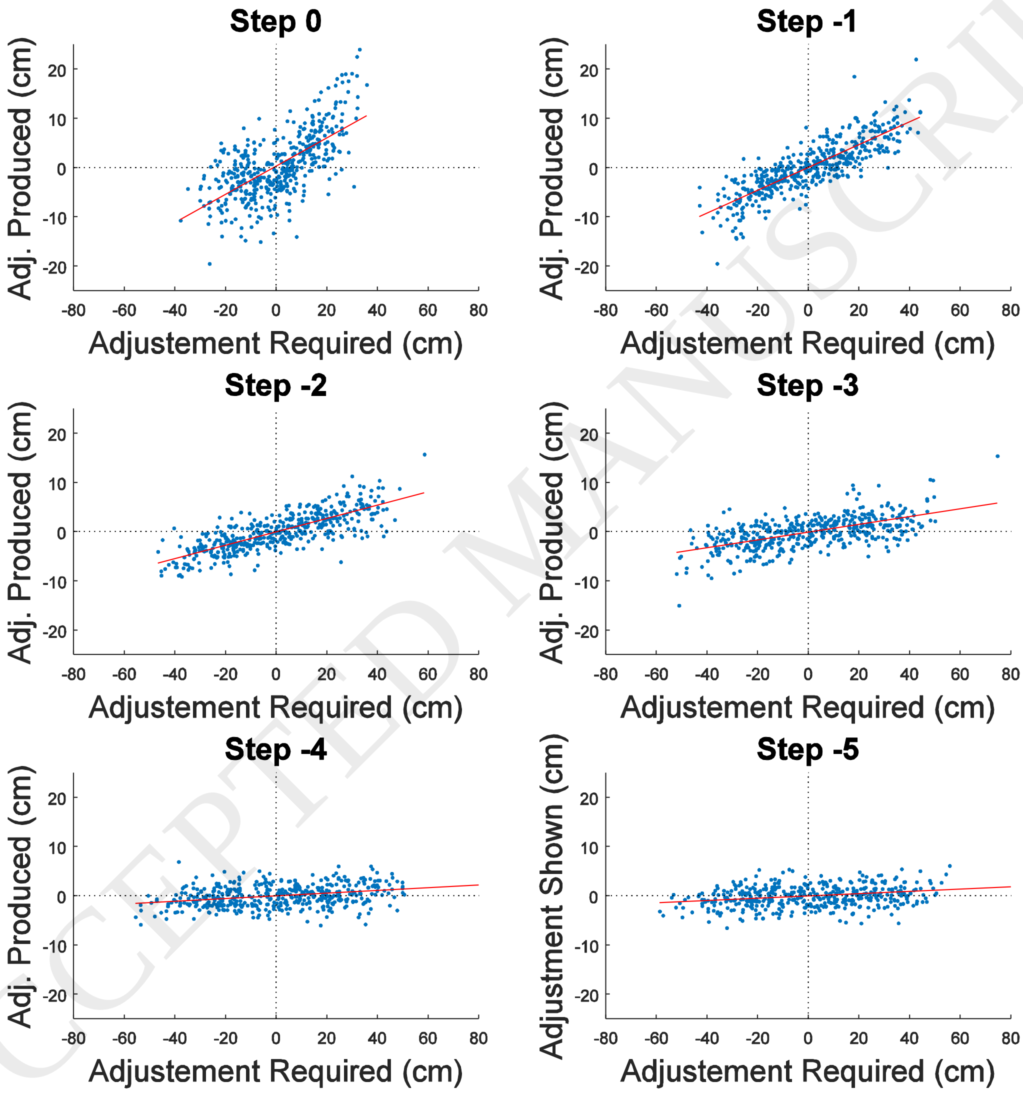

Step 0
Step -1
Step -2
Step -3
Step -4
Step -5
Adj. Produced (cm)
Adjustment Shown (cm)
Adjustement Required (cm)

Table 1. Descriptive information of participants (N=16) gait behavior

	Default Mean (SD)[a]	Range
Step Length (m)	0.77 (0.04)	0.71 to 0.86
Cadence (steps per minute)	111.51 (9.41)	91.16 to 126.52
Velocity (m/s)	1.44 (0.13)	1.17 to 1.80
Number of steps taken between start and step up	11.21 (0.55)	10.21 to 12.30
Start of Regulation (step nr. counting back from step up)	-6.13 (1.31)	-4 to -8

[a] Default step parameters are calculated as the mean of steps early in the trial