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RESEARCH ARTICLE

Slower than normal walking speeds involve a pattern shift in joint and temporal coordination contributions

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Abstract

Kinematic and spatiotemporal gait parameters are known to scale with gait speed, though inter-joint coordination during swing remains consistent, at least across comfortable speeds. The purpose of this study was to determine whether coordination patterns serving limb clearance and shortening change across a range of gait speeds. We assessed 17 healthy adults walking overground at their self-selected speed and multiple, progressively slower speeds. We collected lower extremity kinematics with 3D motion analysis and quantified joint influence, or relative joint contributions, to limb clearance and shortening. We investigated changes in coordination using linear mixed models to determine magnitude and timing differences of joint influence across walking speeds. Joint influences serving limb clearance (hip, knee, and ankle) reduced considerably with slower walking speeds. Similarly, knee and ankle influences on limb shortening reduced with slower walking speeds. Temporally, joint influences on limb clearance varied across walking speeds. Notably, the temporal order of peak hip and knee influences reversed below typical self-selected walking speeds. For limb shortening, the timing of knee and ankle influences occurred later in the gait cycle as walking speed decreased. While relative joint contributions serve limb clearance and shortening scale with walking speeds, our results demonstrate that temporal coordination of limb clearance is altered in healthy individuals as walking speed falls below the range of typical self-selected walking speeds.

Keywords Gait · Coordination · Limb clearance · Limb shortening · Joint influence

Introduction

Humans can walk at a variety of speeds and typically modulate their gait based on environmental and task demands (Warren 2018; Kesler et al. 2005; Sun et al. 1996; Licence et al. 2015). For instance, individuals typically adopt a slower gait speed in the dark, on sloped surfaces, and in crowds (Kesler et al. 2005; Sun et al. 1996). Similarly, concurrent competing task goals, such as increased cognitive load or obstacle negotiation, often coincide with slowed gait (Licence et al. 2015). In contrast, individuals commonly increase their gait speed when in a hurry. This begs the question of whether the coordination of walking differs across gait speeds.

Understanding unique gait characteristics across a range of speeds offers scientific importance but also has implications for gait rehabilitation. Indeed, if the characteristics of walking change across speeds, individuals working to recover walking ability after neurologic injury, such as a stroke or spinal cord injury, may be confronted with learning a new motor behavior rather than re-learning a well-practiced motor task. In addition, gait researchers commonly speed-match, using healthy individuals walking at very slow speeds, for a direct comparison with pathologic gait (Lehmann et al. 1987; Chen et al. 2005; Little et al. 2014). However, some authors argue that muscle activations patterns change at prescribed speeds differing from self-selected walking speed (Sousa and Tavares 2012). Thus, the appropriateness of speed-matching in gait research is still under debate.

Kinematic and spatiotemporal features of gait are known to scale with gait speed, but inter-joint coordination during

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swing is thought to remain consistent across gait speeds (Kirtley et al. 1985; Nymark et al. 2005; Oberg et al. 1994; Stoquart et al. 2008; Shemmell et al. 2007; Mentiplay et al. 2018). However, studies investigating the relationship of gait characteristics to gait speed typically do not include very slow speeds, limiting potential insight regarding this behavior (Kirtley et al. 1985; Oberg et al. 1994; Shemmell et al. 2007). Indeed, when spatiotemporal characteristics of gait have been investigated at very slow gait speeds, the relationship between temporal characteristics and gait speed has been found to differ between very slow and comfortable gait speeds (Smith and Lemaire 2018). It seems reasonable to posit that coordination may differ as walking speed decreases. However, this question remains to be systematically investigated and is the purpose of our study.

We are specifically interested in the inter-joint and temporal coordination patterns involved in limb shortening and limb clearance during the swing phase of gait. Coordinated motion of the stance and swing limbs serves the objective of repositioning the swing limb from behind to in front of the stance limb with sufficient clearance to avoid premature foot contact (Gage 1990; Perry 1992). For this investigation, we focused our study on the timing and magnitude of contributions to limb shortening and limb clearance directly attributable to the sagittal plane joint motions of the swing limb. To determine whether coordination patterns change, we assessed the joint contributions across a range of walking speeds spanning gait speeds consistent with comfortable walking in health to very slow walking.

Methods

Participants

We studied 17 healthy adults (age 44.7 ± 11.3 years; men/women 11/6) free from any cardiac, orthopedic, or neurologic conditions that would limit their ability to walk. All participants provided written informed consent approved by the Stanford University or the University of California, Davis Institutional Review Boards prior to enrollment.

Data collection and processing

We studied participants, while they walked overground at their self-selected speed (SSWS) and up to five progressively slower speeds. Rather than utilizing external constraints (e.g., timing gate, metronome), we instructed the participants to ‘walk slower’, ‘walk even slower’, and if possible, ‘walk even slower’ until participants indicated that they had reached their slowest speed. This approach allowed us to investigate how participants self-organize slower walking behavior and, specifically, the relationship between gait speed and joint influence on limb clearance and limb shortening.

All participants wore their own footwear, typically a flat, athletic style shoe, and their walking was not constrained by external pacing. Three-dimensional marker position data were collected and labeled using two motion capture systems due to laboratory upgrades (Qualisys AB., Gothenburg, Sweden, 200 Hz and OptiTrack, Corvallis, Oregon, 100 Hz). A modified Cleveland Clinic marker set was used (5 clusters and 23 additional markers) as described by Chen and Patten (Chen and Patten 2008). We used Visual 3D x64 Pro (v6.03.0, C-Motion, Germantown, MD) to model and filter (low-pass fourth-order Butterworth, 6 Hz cut-off) marker data, calculate kinematics, and detect gait events. Heel strike and toe off were defined using the ‘coordinate-based treadmill algorithm with application to overground trials’ as described by Zeni et al. (2008). Visual inspection of these gait events ensured that there were no false positives. We time-normalized kinematic data to a 101-point gait cycle and calculated our variables of interest using custom Matlab (MathWorks Version 9.6 R2019a, Natick, MA) scripts.

Biomechanical model

We used a planar model of the leg to investigate the relative contributions of sagittal plane swing limb joint angles to limb clearance and limb shortening (Moosabhoy and Gard 2006). By convention, the model reports hip flexion, knee flexion, and ankle dorsiflexion angles as positive joint rotations. The model used in the current analysis was developed by Moosabhoy and Gard and is described briefly below (Moosabhoy and Gard 2006).

Limb clearance sensitivity

Toe clearance served as our proxy for limb clearance. We used the vertical trajectory of the distal toe marker to quantify toe position. Vertical toe position (i.e., toe height) is a function of: (1) vertical hip position, (2) thigh, shank, and foot segment lengths, and (3) hip, knee, and ankle angles [see Eq. 2 (Moosabhoy and Gard 2006)]. As such, the relative contribution of each joint, or sensitivity, can be determined by calculating the partial derivative of the vertical toe position with respect to each joint angle [see Eqs. 6–8 (Moosabhoy and Gard 2006)]. Interpretation of these values is based on the instantaneous direction of joint motion.

Limb shortening sensitivity

Shortening of the swing limb, rather than an absolute measure of clearance, provides a direct measure of the capacity for limb shortening to enable the swing limb to advance in front of the body without foot-floor contact (Moosabhoy and

Gard 2006). We quantified limb shortening as the percent reduction in normalized limb length relative to the instantaneous height of the hip joint center. Normalized limb length was calculated as the instantaneous hip–toe distance (HTD) divided by the instantaneous vertical distance from the hip joint center to the floor (HFD) (Moosabhoy and Gard 2006). The hip–toe distance is calculated via the Pythagorean theorem using the vertical and fore-aft coordinates of the hip joint center and distal toe marker [see Eq. 15 (Moosabhoy and Gard 2006)]. Normalized limb length values less than 1 indicate limb shortening. Again, the partial derivative of normalized limb length with respect to the contributing joints (i.e., knee and ankle) quantifies the relative contribution of the knee and ankle to limb shortening [see Eqs. 16, 17 (Moosabhoy and Gard 2006)].

Outcomes

Inter-joint coordination

Interpretation of limb clearance and limb shortening sensitivity values requires simultaneous knowledge of the direction of joint motion. For example, at mid-swing, limb clearance sensitivity with respect to knee flexion is positive, suggesting that knee flexion increases limb clearance. However, the knee is extending during this time, and thus, motion at the knee reduces limb clearance around mid-swing (~80% of gait cycle; Fig. 1). Accordingly, we quantified the estimated joint influence on limb clearance (LCI) and limb shortening (LSI) throughout the cycle as the product of sensitivity and the time derivative of the respective joint angle (e.g., hip, knee, and ankle), using the following equation:

$$I_i = S_i \times \left(A_i - A_{i-1}\right) \times \mathrm{SF}, \quad (1)$$

where I_i is the influence value, S_i is the sensitivity value, A_i is the sagittal plane joint angle at time i, and SF is the sampling frequency used to capture the marker data. Importantly, i represents one sample frame of time. It follows that positive influence values for limb clearance indicate that the specified joint increases limb clearance. For limb shortening, a negative influence value indicates shortening of the limb by the given joint.

Previous studies of toe clearance and fall risk in healthy elders investigated toe clearance in mid-swing (Murray and Clarkson 1966; Begg et al. 2007) and late swing (Mills et al. 2008). However, we noted that the critical toe clearance, identified by a local minimum of the vertical trajectory of the toe in mid-swing (Winter 1992; Moosabhoy and Gard 2006; Murray and Clarkson 1966; Begg et al. 2007), is often absent in healthy controls when walking at slow speeds (Fig. 2) (Santhiranayagam et al. 2017). Thus, to maintain consistency throughout our sample, all influence values were investigated at peaks relevant to the task goals

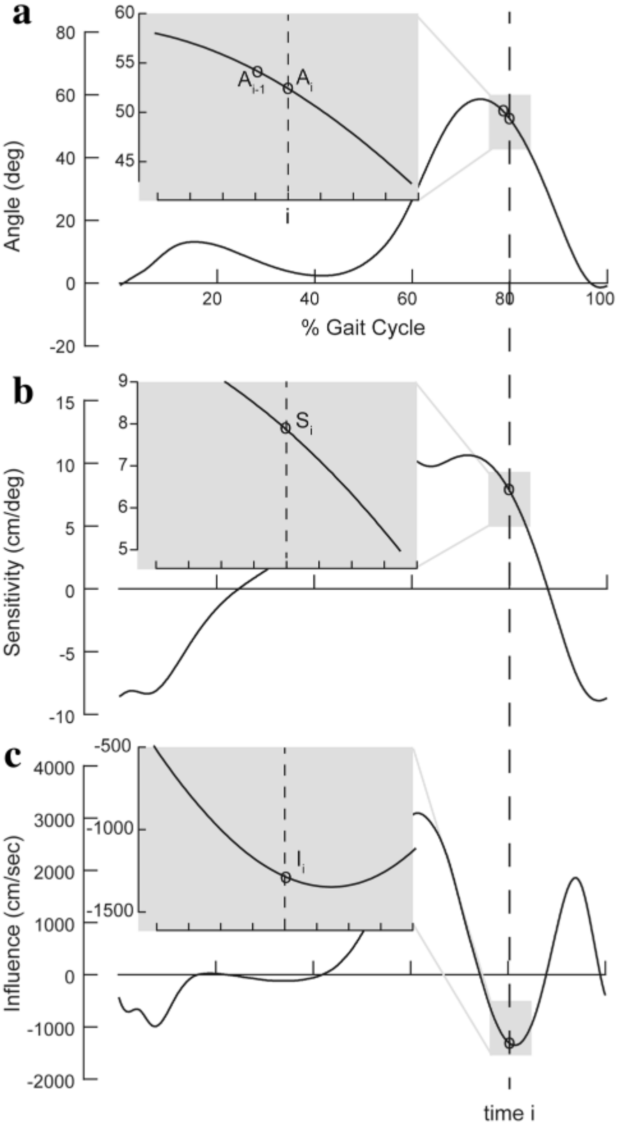

Fig. 1 Quantification of joint influence. The relationship between: **a** sagittal plane joint angle, **b** limb clearance sensitivity, and **c** limb clearance influence, illustrated using group mean data at self-selected walking speed. Estimated joint influence on limb clearance (LCI) and limb shortening (LSI) throughout the gait cycle is quantified using the following general equation: $I_i = S_i \times (A_i - A_{i-1}) \times \mathrm{SF}$; where I_i is the influence value, S_i is the sensitivity value, and A_i is the sagittal plane joint angle, all at time i represented by the dashed vertical line throughout all subplots. SF is the sampling frequency used to collect the data. Shaded gray regions at time i highlight individual equation components; these are expanded in insets to illustrate greater detail between 76 and 84% of the gait cycle. Incorporation of the direction of joint motion facilitates interpretation of sensitivity values. Specifically, at time i, the sensitivity value (subplot **b**) is positive, suggesting that joint motion increases limb clearance. However, because the joint is extending (subplot **a**), the influence value is negative, indicating that the joint motion at time i reduces limb clearance

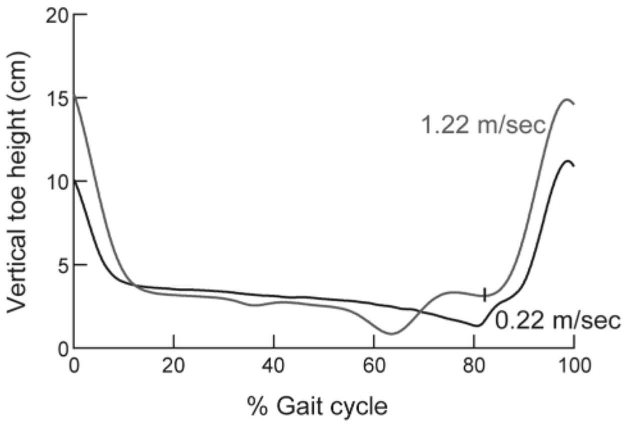

Fig. 2 Vertical toe height. The vertical trajectory of the great toe marker, time-normalized to the gait cycle, illustrates limb clearance. Data are from a single subject walking at their self-selected walking speed (1.22 m/s; gray) and a very slow walking speed (0.22 m/s; black). The local minimum (denoted with vertical hashmark) of the vertical trajectory of the great toe marker, typically used to identify critical toe clearance in mid-swing, is absent at slow walking speeds in some individuals, as illustrated here. For limb clearance, the first hip influence peak (negative) occurred near toe off, and the first peaks for the knee and ankle (positive) occurred near toe off and during mid-swing, respectively (see Figs. 3 and 4, respectively)

of limb clearance and limb shortening. For limb clearance (Fig. 3a): (1) the hip influence peak was negative and typically occurred near toe off, (2) the knee peak was positive and typically occurred near toe off, and (3) the ankle peak was positive and occurred around mid-swing. For limb shortening (Fig. 4a), both influence peaks investigated were negative and occurred within the first half of swing.

We investigated the joint influences of limb clearance and limb shortening as they relate to gait speed. Understanding these concurrent relationships allows us to describe how the inter-joint coordination, or relative joint contributions to limb clearance and limb shortening, may differ across walking speeds.

Temporal coordination

To assess the temporal coordination pattern between joints, we also investigated the timing of peak influence for each joint, relative to the gait cycle. We identified altered temporal coordination in a manner consistent with inter-joint coordination.

Statistical analysis

We tested for differences between legs for each variable/joint combination with Student's paired *t* tests. All *t* tests were non-significant (p's ≥ 0.01) using the Holm–Bonferroni adjusted α-level (initial p value < 0.0045); therefore, we pooled the data from both legs for all analyses. For all remaining variables, we used Goodness of Fit to test for normality and Levene's test to assess equality of variances. Minor violations were noted for the parametric assumptions of normality and homogeneity of variances (p's > 0.05).

To accommodate these violations, we used linear mixed models to determine if the fixed effects of gait speed, joint, and the interaction between gait speed and joint were significant predictors of peak limb clearance and limb shortening influences (Quené and van den Bergh 2004). In each of these models, we included random effects including intercepts for each joint and by-joint random slopes for the effect of gait speed (Winter 2013). Finally, we used the Unequal Variance covariance structure with multiple repeats for each subject. To understand the non-linear

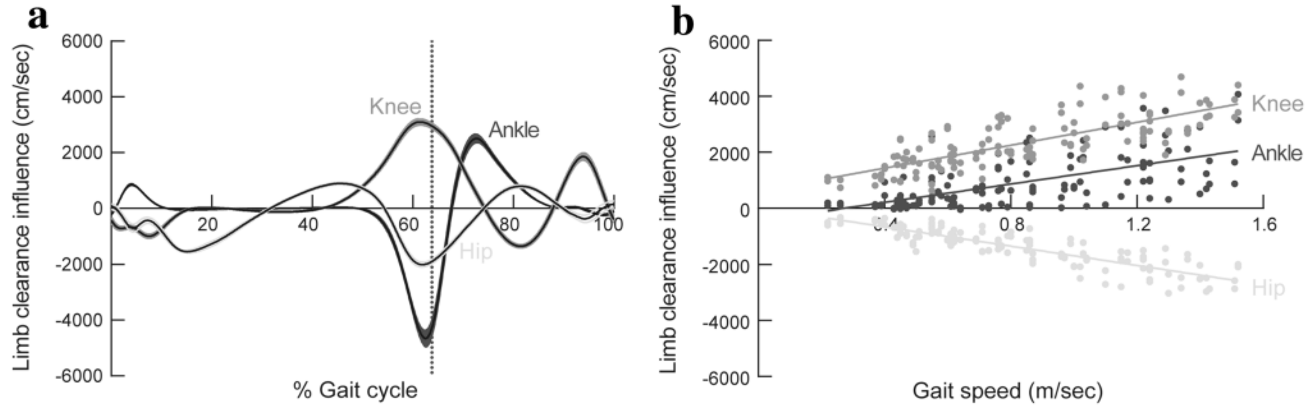

Fig. 3 Limb clearance influence. **a** The general pattern of limb clearance influence, time-normalized to the gait cycle, is depicted with respect to the hip, knee, and ankle. Data are mean ± SEM at self-selected walking speeds. Dotted vertical line represents timing of toe off. The peaks quantified for analysis include: (1) hip (negative peak), (2) knee (1st positive peak), and (3) ankle (positive peak). Positive influence values for limb clearance indicate that the specified joint increases limb clearance. **b** Peak limb clearance influence represented across gait speeds with notable increases in peak hip influence and decreases in peak ankle and knee influences, as speed is reduced

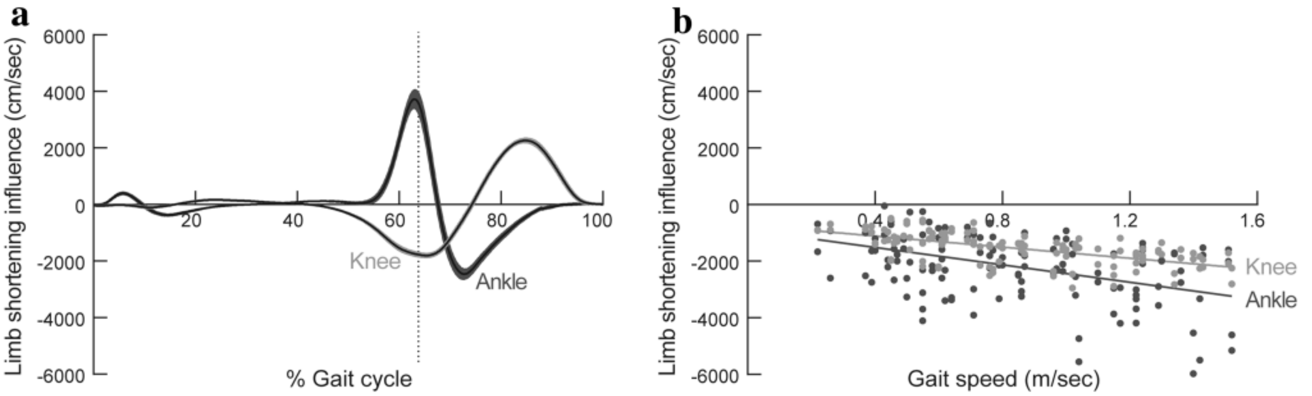

Fig. 4 Limb shortening influence. **a** The general pattern of limb shortening influence, time-normalized to the gait cycle, is depicted with respect to the knee and ankle. Data are mean ± SEM at self-selected walking speeds. Dotted vertical line represents timing of toe off. The peaks quantified for analysis occur during swing as follows: (1) knee (negative peak), and (2) ankle (negative peak). Positive influence values for limb shortening indicate lengthening of the limb by the given joint. **b** Peak limb shortening influence represented across gait speeds with systematic decreases in knee and ankle influences as speed is reduced

trend apparent in our timing variables, we assessed the appropriateness of a quadratic term (gait speed × gait speed) in the linear mixed models used to identify predictors of the timing of peak influences with respect to (wrt) the gait cycle.

As an exploratory analysis to determine if the temporal order of hip and knee influences on limb clearance shifted across gait speeds, we calculated the difference between knee and hip influence timing relative to the gait cycle. Positive values of timing difference indicate that the knee influence occurs later in the gait cycle than the hip influence. We used a linear mixed model with a fixed effect of gait speed, allowing for varying intercepts by subject, and the Unequal Variance covariance structure with multiple repeats for each subject to determine the relationship between gait speed and the difference between knee and hip influence timings.

In total, we performed five linear mixed models; to correct for multiple comparisons, we utilized the Holm–Bonferroni method with a target of $\alpha = 0.05$ to calculate adjusted α levels for all variables (Holm 1979). When we identified significant interactions, we conducted separate models for each joint removing the main effect of joint and the interaction term involving joint to investigate unique relationships by joint. The α level applied for each model was carried through and used for the respective models. All statistical tests were performed with JMP® Pro 14.0.0 (SAS Institute Inc., Cary, NC).

Results

Our participants produced a range of walking speeds: 0.22–1.52 m/s.

Inter-joint coordination

Limb clearance

At typical walking speeds, the primary swing limb joint contributions to limb clearance are characterized by a dynamic interplay between hip and knee flexion; while knee flexion is the primary contributor to limb clearance, hip flexion counters this objective when the limb is posterior to the trunk in early swing (Fig. 3a). Our overall model confirmed that the fixed effects of joint ($F_{(2,46.3)} = 341.6$; $p < 0.0001$), gait speed ($F_{(1,46.3)} = 42.0$; $p < 0.0001$), and the interaction between joint and gait speed ($F_{(2,43.7)} = 166.0$; $p < 0.0001$) were significant predictors of limb clearance influences. Individual joint models revealed the fixed effect of gait speed to be a consistently significant predictor of limb clearance influence. While these findings suggest that the influence of sagittal plane joint motion varies across gait speeds, these relationships differ by joint (Fig. 3b). The relationship of the knee and ankle influences on limb clearance reveals large positive slopes ($b_{\text{knee}} = 21.69$, $p < 0.0001$; $b_{\text{ankle}} = 14.87$, $p < 0.0001$); whereas the relationship of the hip influence on limb clearance is characterized by a large negative slope ($b_{\text{hip}} = -17.53$; $p < 0.0001$).

Limb shortening

The knee and ankle each provide relatively equivalent contributions to limb shortening (Fig. 4a). Our overall model confirmed that the fixed effects of joint ($F_{(1,30.3)} = 9.7$; $p < 0.0041$), gait speed ($F_{(1,27.8)} = 66.9$; $p < 0.0001$), but not the interaction between joint and gait speed($F_{(1,27.8)} = 2.1$; $p = 0.16$) were significant predictors of limb shortening influences. The magnitude of joint influence of limb shortening reduces as gait speed declines (Fig. 4b).

Temporal coordination wrt the gait cycle

For limb clearance, the ankle influence occurs later (70–92%) in the gait cycle than the knee (58–79%) and hip (58–79%) influences (Figs. 3a and 5a–c). For limb shortening, the timing of ankle (63–82%) and knee (60–81%) influences occurs in closer temporal proximity, with the knee influence typically preceding the ankle influence (Figs. 4a and 5e).

The final model for the timing of joint influence on limb clearance revealed that the fixed effects of joint ($F_{(2,51.6)} = 670.7$, $p < 0.0001$), gait speed ($F_{(1,36.9)} = 105.8$, $p < 0.0001$), and a quadratic term for gait speed ($F_{(1,216.5)} = 73.7$; $p < 0.0001$) were significant predictors of the timing of limb clearance influences, although there was not a significant interaction between joint and gait speed ($F_{(2,33.7)} = 0.19$, $p = 0.82$). At typical walking speeds, the peak influence from the knee immediately precedes the peak hip influence, followed considerably later by the peak ankle influence (Fig. 5a–d). While still tightly coupled, our exploratory analysis revealed a reversal of the temporal order

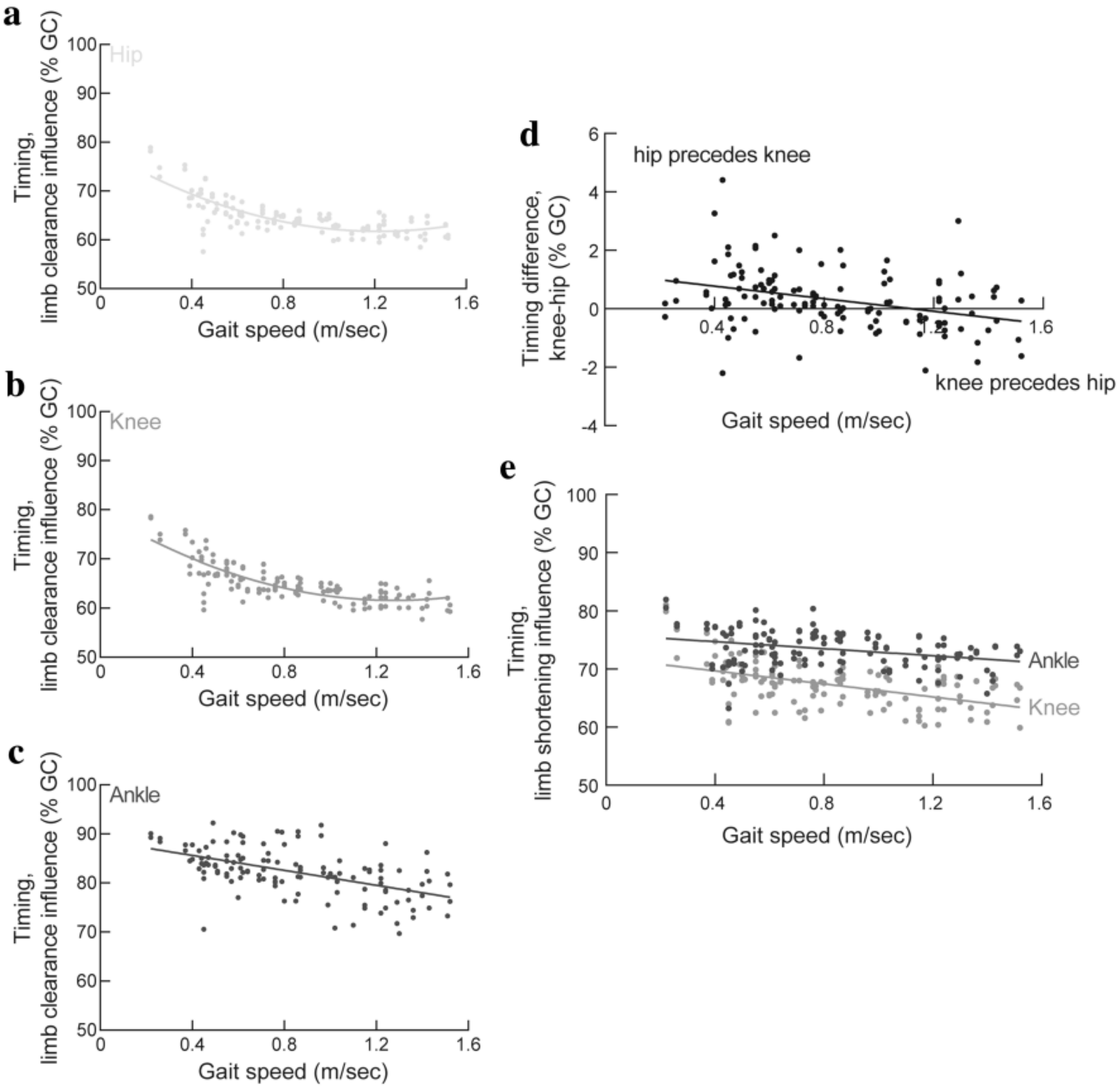

Fig. 5 Timing of peak influences with respect to the gait cycle. The timing of peak limb clearance influences represented across gait speeds for the **a** hip, **b** knee, and **c** ankle. Note, for limb clearance, the peak knee influence immediately precedes the peak hip influence at the higher end of typical walking speeds; this temporal pattern reverses as walking speed falls below the range of typical self-selected walking speeds. **d** The temporal difference between peak influence from the knee and hip illustrates a reversal in the temporal order of knee and hip influences. **e** The timing of peak limb shortening influences represented across gait speeds. The peak knee and ankle influences on limb shortening occur later in the gait cycle at slower walking speeds

of the peak hip and knee influences that occurs as walking speed falls below the range of typical self-selected walking speeds ($F_{(1,56.1)} = 37.0$; $p < 0.0001$; Fig. 5d).

Regarding the timing of joint influence on limb shortening, the final model revealed that the fixed effects of joint ($F_{(1,32.6)} = 80.9$; $p < 0.0001$), gait speed ($F_{(1,24.3)} = 38.7$; $p < 0.0001$), and a quadratic term for gait speed ($F_{(1,205.0)} = 10.8$; $p = 0.0012$) were significant predictors, although the interaction of joint × gait speed ($F_{(1,22.8)} = 2.3$; $p = 0.15$) was not.

Discussion

Overview

Our data reveal changes in the temporal coordination and the relative joint contributions for limb clearance and limb shortening as speed falls below the typical range of normal walking speeds. Regarding limb clearance, the temporal coordination between the hip and knee reversed below typical self-selected walking speeds; in addition, the magnitude of each of the joint contributions reduced with slower walking speeds. This combination of changes revealed similar contributions from the hip and ankle at very slow walking speeds with motion from the knee still contributing the dominant influence over limb clearance. For limb shortening, the knee and ankle contributions were reduced in magnitude with slower walking speeds. In general, the ankle contribution followed the knee contribution; the timing of each scaled with walking speed.

Methodological context

Prior work has used experimental manipulation of walking speeds within a sample to demonstrate the relationship between gait characteristics and gait speed (Nymark et al. 2005; Oberg et al. 1994; Stoquart et al. 2008). Here, we studied a group of individuals walking at their self-selected walking speed and multiple, progressively slower self-paced speeds to investigate coordination over a range of walking speeds. By allowing participants to determine their progressively slower speeds, they were able to self-organize their walking behavior according to their individual biomechanical constraints.

At slow walking speeds, the local minimum of the toe marker trajectory that typically characterizes minimal toe clearance (MTC) (Moosabhoy and Gard 2006; Murray and Clarkson 1966; Begg et al. 2007) is often absent (Santhiranayagam et al. 2017). Indeed, in our sample, the local minimum of limb clearance observed at comfortable walking speeds was absent during very slow walking. Therefore, we investigated peaks of influence serving limb clearance and shortening, rather than investigating influence at a given gait event. As a result, we captured the relationship between the maximal contributions from the hip, knee, and ankle for limb clearance and the knee and ankle for limb shortening.

The influence values investigated here were derived from kinematic data. The magnitude of kinematic excursions is known to vary with gait speed, i.e., smaller joint motions are produced with slower walking speeds (Kirtley et al. 1985; Nymark et al. 2005; Oberg et al. 1994; Stoquart et al. 2008; Mentiplay et al. 2018); our data are consistent with these prior observations. We noted linear reductions in the magnitude of joint influence as walking speed decreases for each joint contributing to limb clearance and limb shortening.

Pattern of joint contributions to limb clearance and limb shortening

Visual inspection of the influence curves (Fig. 3a) reveals that the knee influence over limb clearance is positive at the beginning of swing; in contrast, the hip begins by reducing limb clearance early in swing and then contributes to increased limb clearance during mid-swing when the knee influence is negative. The absolute magnitudes of these influences decrease with slower walking speeds (Fig. 3b). Similarly, the knee and ankle influences over limb shortening (Fig. 4) have significant positive contributions (negative peaks) that decrease with slower walking speeds. The peak knee influence occurs as swing begins and is quickly followed by the peak ankle influence.

Consistent with prior work, our results demonstrate that knee and ankle motion are the primary sagittal plane drivers of limb clearance, while hip flexion negatively impacts limb clearance immediately following toe off (Winter 1992). However, any joint motion in the stance or swing limbs, and the muscles that control those motions, can contribute to limb clearance. As an example of this critical point that limb clearance results from a multitude of factors, frontal plane pelvic motion, specifically contralateral hip abduction, has been shown to be highly influential on limb clearance (Winter 1992). Our current model accounted for only the sagittal plane motion of the swing limb, which thus cannot provide a complete picture of the three-dimensional and contralateral contributions to limb clearance. However, our findings do reveal a clear indication of the relationship between swing limb joint motions and limb clearance and limb shortening.

Does coordination change across walking speeds?

Prior work has noted the relationships between gait speed and certain spatiotemporal characteristics of gait differ at walking speeds < 0.5 m/s (Smith and Lemaire 2018). Here, we investigated whether temporal or inter-joint coordination changed between typical self-selected walking speeds and slower walking speeds.

Temporal coordination of the walking pattern changed as gait speed decreased. Similar to other reports, we found the timing of peak influences on limb clearance from the hip and knee which are tightly coupled under all walking conditions with the knee influence immediately preceding the hip influence (Hershler and Milner 1980; Charteris 1982; Leroux et al. 1999; Awai and Curt 2014). However, the temporal order of hip and knee influence reverses as speed falls below the typical range of self-selected gait speeds. The interpretation of this temporal reversal remains speculative and warrants investigation with a larger sample to better understand possible implications. Of note, all of our participants were comfortably able to produce walking speeds faster and slower than the speed at which we noted the temporal reversal to occur, suggesting that healthy individuals are able to switch between coordination patterns as needed. However, many of our participants struggled, or were unable, to produce walking speeds < 0.5 m/s, thus reinforcing the idea that very slow walking may, indeed, constitute a different motor program (Leiper and Craik 1991; Smith and Lemaire 2018). Due to our participants' limited ability to walk at these very slow speeds, we can neither substantiate nor refute this idea at this time, although it is worthy of future investigation with implications for gait rehabilitation and research.

Influence values, as used here, represent more than the magnitude of joint excursion. Influence represents the relational contribution of the joint excursion to the functional tasks of limb clearance and limb shortening (Little et al. 2014); that is, the concurrent coordination between joints to achieve a task goal. Furthermore, influence quantifies the respective joint contributions that are temporally linked to their task goal throughout the gait cycle. We observed significant reductions in the magnitude of hip, knee, and ankle joint influence with slower walking speeds. These changes are consistent with a linear scaling noted in other kinematic features as gait speed is reduced (Kirtley et al. 1985), rather than a change to the fundamental coordination pattern.

Our findings are consistent with the significant body of work illustrating that the nervous system controls the endpoint of the limb trajectory whereby motion of distal limb segments is more invariant than proximal segments (Ivanenko et al. 2002a, b, 2007, 2008; Bosco et al. 2000). Endpoint control explains the remarkable constancy noted in the relationship between limb velocity and endpoint trajectory across speeds ranging from 0.19–1.39 m/s (Ivanenko et al. 2002b). This range of speeds is generally consistent with the speeds produced in our study. Our data illustrate the magnitude of joint influences adjust to achieve sufficient limb clearance and limb shortening to meet the task demand.

Significant implications for aging

Our findings also reveal significant implications regarding age-related changes in gait. Not only do older adults walk slower than their younger counterparts, but alterations in intralimb coordination with aging have also been described (Noce Kirkwood et al. 2018; Byrne et al. 2002; Winter 1991). The challenges we noted during very slow walking, coupled with the coordination changes attributable to aging, may combine significantly increasing the challenge of slow walking to the point it is unachievable for some. This premise was advanced by Leiper and Craik following observation that the ability of older adults to modulate walking to very slow speeds was systematically related to physical activity levels (Leiper and Craik 1991). Further investigation of this phenomenon is indicated.

Is speed-matching in biomechanical analyses appropriate?

Speed-matching is commonly used to provide appropriately scaled normative values when comparing gait parameters between individuals with pathology and non-disabled controls (Chen et al. 2005). Of note, the slowest gait speeds studied here were exceptionally slow speeds for healthy individuals, but match well with gait speeds observed in clinical populations (Olney et al. 1994; Chen and Patten 2008). Observation of altered coordination patterns motivates careful consideration of the outcome measures used for the study of pathologic gait to determine appropriateness of speed-matching. Kinematic measures and certain spatiotemporal variables tend to maintain a consistent relationship with gait speeds, even at very slow walking speeds (Nymark et al. 2005; Stoquart et al. 2008; Mentiplay et al. 2018). For assessment of these metrics, speed-matching is both appropriate and necessary to differentiate persistent gait deviations attributable to pathology rather than walking speed alone (Jonkers et al. 2009; Chen et al. 2005). The changes we noted in temporal coordination also support speed-matching when investigating temporal components of gait or the muscle activations driving the task. It remains to be seen whether coordination patterns adapt and the time required achieving stable, steady-state performance. The extent to which muscle activation patterns change similarly to support the temporal reversal we noted remains unknown. These are potential areas for future study.

Conclusion

Our data illustrate that the temporal coordination of joint contributions serving limb clearance changes as speed falls below typical walking speeds. In contrast, the magnitude of the joint contributions decreases linearly with slower walking speeds suggesting a scaling phenomenon consistent with kinematic and spatiotemporal changes noted at slower walking speeds. Our findings provide new insight regarding temporal coordination across gait speeds and have significant implications for the study of pathologic gait.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Research involving human participants All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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