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Coordination of push-off and collision determine the mechanical work of step-to-step transitions when isolated from human walking

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ABSTRACT

In human walking, each transition to a new stance limb requires redirection of the center of mass (COM) velocity from one inverted pendulum arc to the next. While this can be accomplished with either negative collision work by the leading limb, positive push-off work by the trailing limb, or some combination of the two, physics-based models of step-to-step transitions predict that total positive work is minimized when the push-off and collision work are equal in magnitude. Here, we tested the importance of the coordination of push-off and collision work in determining transition work using ankle and knee joint braces to limit the ability of a leg to perform positive work on the body. To isolate transitions from other contributors to walking mechanics, participants were instructed to rock back and forth from one leg to the other, restricting motion to the sagittal plane and eliminating the need to swing the legs. We found that reduced push-off work increased the collision work required to complete the redirection of the COM velocity during each transition. A greater amount of total mechanical work was required when rocking departed from the predicted optimal coordination of step-to-step transitions, in which push-off and collision work are equal in magnitude. Our finding that transition work increases if one or both legs do not push-off with the optimal coordination may help explain the elevated metabolic cost of pathological gait irrespective of etiology.

1. Introduction

Walking is often a difficult task for those suffering from pathological gait disorders such as stroke, spinal cord injury or amputation. One reason for the difficulty is that pathological gait can require more than twice the metabolic energy of healthy gait [1,2]. A reasonable focus for gait rehabilitation is the recovery of mechanisms that reduce metabolic cost [3]. To accomplish this, one must first understand the important mechanisms that underlie the metabolic cost of healthy walking and how they are compromised in gait pathologies.

Step-to-step transitions appear to be an important determinant of the mechanical work and metabolic cost of healthy walking. The single support phase of walking is characterized by center of mass (COM) motion similar to that of an inverted pendulum [4] and each transition to a new stance limb requires redirection of the COM velocity from one inverted pendulum arc to the next [5,6]. Healthy subjects accomplish this redirection with nearly equal amounts of positive push-off work by the trailing limb and negative collision work by the leading limb [6]. This transition work accounts for approximately two thirds of metabolic cost when walking at a moderate speed [7].

Physics-based models of the step-to-step transition predict that the coordination of push-off and collision work has a strong effect on total mechanical work. While redirection of the COM velocity can be accomplished in these models with negative collision work by the leading limb, positive push-off work by the trailing limb, or some combination of the two, total work is minimized when the push-off and collision work are equal in magnitude [7–9]. This optimal coordination minimizes the total mechanical work performed by these models because push-off assists in redirecting the COM velocity so that the leading leg needs to perform less negative work to complete the redirection. Without push-off, up to four times the energy is lost in redirecting the COM velocity [8,9]. This prediction has direct implications for pathological gait irrespective of etiology: for a given walking speed, step-to-step transition work, and perhaps metabolic cost, may increase if one or both legs cannot push-off with the optimal magnitude [3].

The purpose of the present study was to test the importance of the coordination of push-off and collision work in determining the mechanical work required for step-to-step transitions. To isolate transitions from other contributors to walking mechanics, we instructed participants to rock back and forth from one leg to the other, restricting motion to the sagittal plane (Fig. 1A). Although

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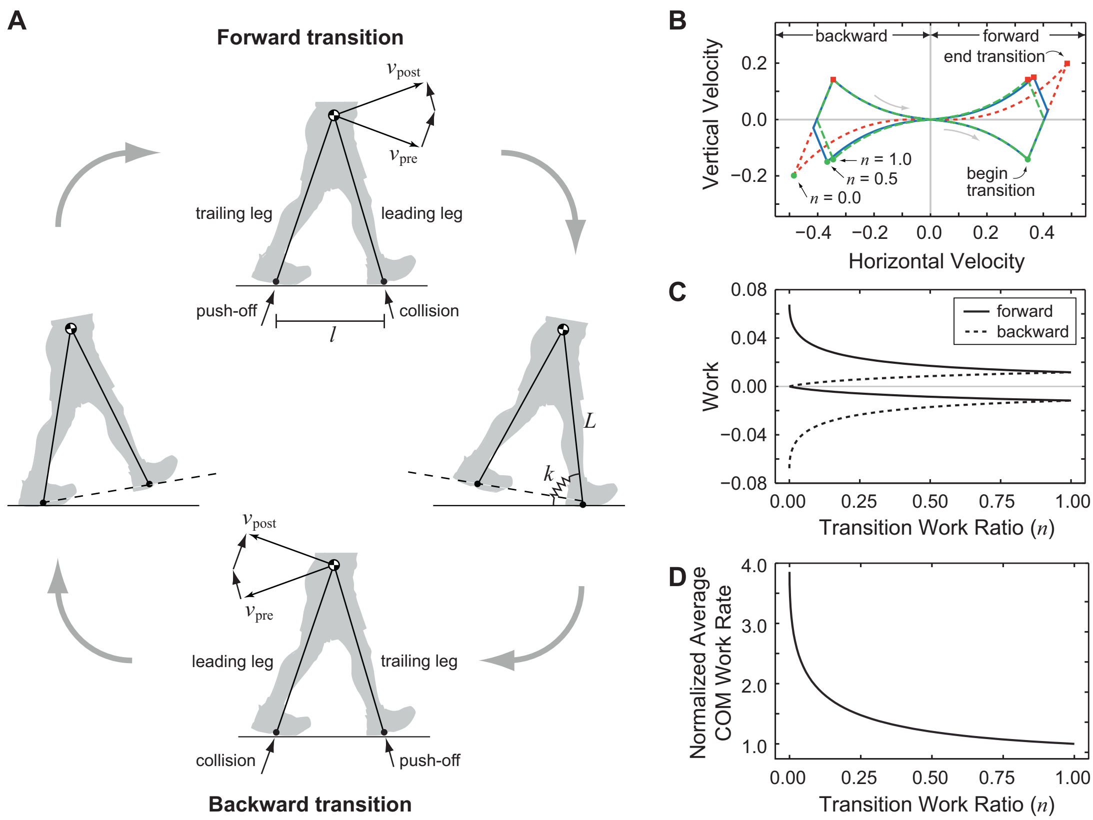

Fig. 1. Model. (A) A physics-based model of sagittal plane rocking consisting of mass-less rigid legs of length L fixed rigidly to a point-mass pelvis. During single support phases, the system behaves as a single degree of freedom inverted pendulum. During the transition between single support phases, the COM velocity is redirected from the pre-transition velocity, $\boldsymbol{v}_{pre}$, to post-transition velocity, $\boldsymbol{v}_{post}$, using an impulsive push-off force acting along the trailing leg followed immediately by an impulsive collision force acting along the leading leg. A full rocking cycle consists of forward and backward half-cycles, defined by the direction of the COM velocity. Transitions between inverted pendulum phases occur in the middle of each half cycle with the front leg leading during the forward transition and the back leg leading during the backward transition. The step length, l, is determined by the angle between the legs. To keep the duration of forward and backward half-cycles equal, the front leg is actuated using a simple linear spring, k. (B) Hodographs illustrate the COM velocity changes at a step length of 0.8 L for three different transition work ratios, n, illustrated by the three different line styles. (C) Forward and backward push-off and collision work depend on the transition work ratio. Positive and negative values indicate push-off and collision work, respectively. When $n = 1$, the COM velocity is redirected during the forward and backward transitions with equal amounts of forward and backward push-off work. When $n = 0$, the front leg performs no push-off work during the backward transition relying entirely on the back leg push-off work during the forward transition to power the rocking motion. (D) The coordination of push-off and collision work has a strong effect on the total positive mechanical work required to rock. Here, the total positive mechanical work performed throughout the entire rocking cycle is divided by cycle duration and normalized for the value at $n = 1$.

rocking eliminates the need to swing the legs and progress forward, our recent research has demonstrated that the mechanics of rocking and walking transitions are remarkably similar in that they share the following characteristics: (a) the trailing leg performs positive push-off work while the leading leg performs negative collision work, (b) work is performed mainly during the transition periods, (c) the COM work rate increases strongly with step length, and (d) the increases in average COM work rate exact a proportional metabolic cost [10].

To limit the ability of the front and back legs to perform positive work on the body, we used immobilization braces to restrict the motion of the front and back ankle and knee joints, respectively (Fig. 2). We tested the hypothesis that, irrespective of which leg is immobilized, reducing push-off work will increase the collision work required to complete the redirection of the COM velocity during the transitions. More specifically, reducing push-off work by the back leg will increase the collision work required of the front leg when rocking forwards. Similarly, reducing the push-off work by the front leg will increase the collision work required of the back leg when rocking backwards.

We also hypothesized that a departure from the predicted optimal coordination of step-to-step transitions, in which push-off and collision work are equal in magnitude, increases the total mechanical work required to rock. Our previous research found that people prefer to rock with sub-optimal transition work coordination—they performed considerably more back leg push-off work, and less front leg collision work, when rocking forwards and less front leg push-off work, and more back leg collision work, when rocking backwards [10]. This preference was not unexpected—people choose to move in a manner that minimizes metabolic cost and mechanical work is only one contributor to total energy expenditure. This is also true in walking where transition work is minimized with infinitely short and narrow steps but people prefer finite step lengths and widths in order to minimize metabolic cost [11,12]. The implication of the preference for sub-optimal transition work coordination in rocking is that it is not possible to predict the exact effect of restricting the back leg ankle and knee joints on total mechanical work. While a complete elimination of back leg push-off work will bring rocking even further from the optimal coordination pattern increasing the total mechanical work required to rock, a partial reduction may bring subjects closer to the optimal coordination pattern and reduce the total mechanical work. The predicted effect of immobilizing the front leg is clearer. Because people prefer to perform less push-off work with the front leg when rocking backwards, restricting its joints will cause a further departure from the optimal transition work coordination and increase the total mechanical work. Before describing the experiments in more detail, we use a simple physics-based model to motivate our hypotheses and predict how rocking dynamics depend on the coordination of transition work.

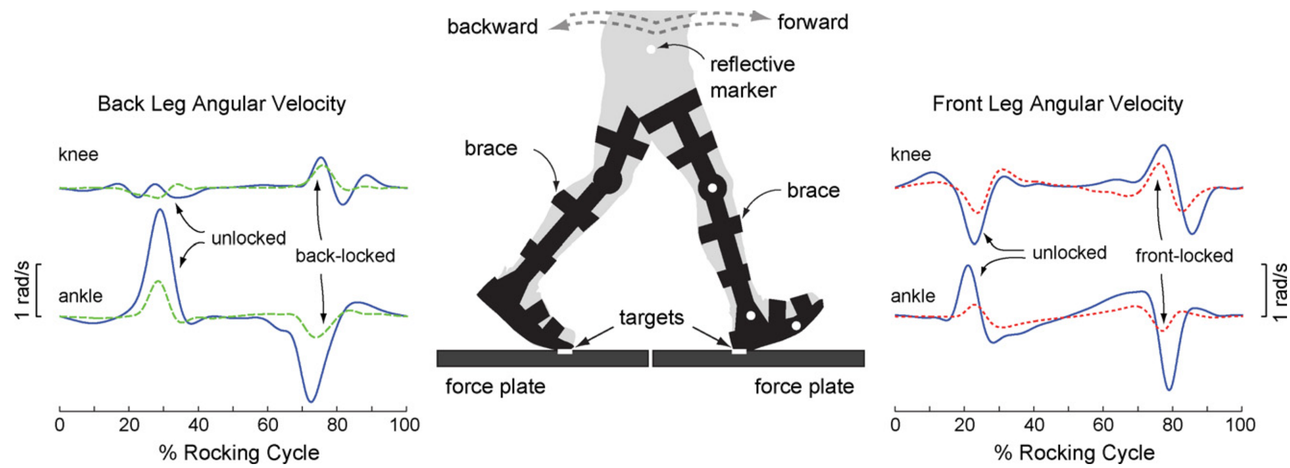

Fig. 2. Experimental design. As illustrated in the middle panel, force plates measured the individual limb ground reaction forces while participants rocked back and forth from one leg to the other. They rocked at a constant step length (0.8 L), enforced using targets mounted on the force plates. In all trials, participants wore commercially available ankle and knee braces on both their front and back legs. Analysis of the motion of reflective markers attached to the limb joints confirmed that these braces effectively limited joint motion when locked. The left panel illustrates the reduction in the back ankle joint and back knee joint angular velocities in the back-locked condition—where the back ankle and knee joints were locked while the front ankle and knee were free to rotate—compared to the unlocked condition—where the ankle and knee joints of both the back and front legs were free to rotate. The right panel compares the angular velocity of the front ankle and knee joints in the front-locked condition to the unlocked condition. The presented data is the average across all participants.

2. Materials and methods

2.1. Model

In this model of back and forth rocking (Fig. 1), the COM velocity has to be redirected during each transition with some combination of push-off work by the trailing leg and collision work by the leading leg. To quantify the coordination of the COM velocity redirection, we used the transition work ratio n, previously defined as the ratio of backward push-off work to forward push-off work [10]. In this model, n has two additional and equivalent definitions: (a) the ratio of forward collision work to forward push-off work, and (b) the ratio of backward push-off work to backward collision work. To understand how the coordination of the COM velocity redirection affects rocking dynamics, we varied n between 0 and 1 by making the backward transition push-off work a fraction of the forward transition push-off work. Whenever forward push-off exceeded backward push-off ($n < 1$), the model moved faster after the forward transition when compared to the backward transition (Fig. 1B). To keep the duration of forward and backward half-cycles equal, we actuated the front leg inverted pendulum phase using a simple linear spring with stiffness k [10]. We simulated rocking cycles at different transition work ratios (0–1) and fixed step lengths, adjusting k and the initial conditions to find steady state cycles with equal half-cycle durations.

Analysis of the model demonstrated that while steady state rocking is possible at all transition work ratios, rocking dynamics depended strongly on the available push-off work. When $n = 1$, both the forward and backward transitions were accomplished with push-off and collision work of equal magnitude (Fig. 1B and C). In contrast, the front leg was restricted from performing push-off during the backward transition when $n = 0$ requiring the COM velocity redirection to be accomplished entirely with negative collision work by the back leg. The net negative work during the backward transition was balanced by net positive work during the forward transition with the COM velocity redirected entirely with push-off work from the back leg. A greater amount of total positive mechanical work was required in this rocking model when there was an unequal division of push-off work between the forward and backward transitions (Fig. 1D).

The increases in total positive work were due to the combined effects of: (a) the increase in the positive push-off work required by the trailing limb to redirect the COM velocity when the redirection is not assisted by negative work by the leading limb, which is only partially compensated by a reduction in the positive work required during the subsequent transition; (b) the backward pre-transition velocity increasing with a reduction in work ratio (Fig. 1B) requiring more work to complete the COM velocity redirection; and (c) the front leg actuation by the spring, required during single support when the work ratio is less than unity, contributing to the total positive work required to rock [10]. There was a very large penalty when front leg push-off was eliminated entirely, the total required work increased by 286% for $n = 0$ when compared to $n = 1$. This nearly three fold increase was reduced to a more modest 20% penalty when $n = 0.5$ illustrating that a little bit of push-off work went a long way toward reducing the total mechanical work. This general pattern was independent of step length, l.

2.2. Experimental procedures

Eight healthy participants (7 males and 1 female; age 28.0 ± 3.6 years; mass 74.8 ± 10.6 kg; leg length 0.92 ± 0.04 m; mean ± standard deviation) wore commercially available ankle and knee braces on both their front and back legs (ProGait ST Boot, Bledsoe Brace System, Grand Prairie, Texas). In the *unlocked condition*, both ankle and knee joints were free to rotate—the resistance to motion was negligible. In the *front-locked condition*, the front ankle brace locked the front ankle at 110° of extension, the front knee brace locked the front knee at 180° of extension, and the back leg ankle and knee joints were free to rotate. In the *back-locked condition*, the back ankle brace locked the back ankle at 90° of extension, the back knee brace locked the back knee at 180° of extension, and the front leg ankle and knee joints were free to rotate. Participants completed these three conditions in random order. Fig. 2 illustrates that these braces effectively limited joint motion.

Participants rocked at a constant step length (0.8 L), enforced by asking participants to contact two appropriately-spaced markers with their front foot heel and back foot toe. We enforced a constant dimensionless rocking frequency of 0.50 (25 cycles per minute, on average) by asking participants to match both their front and back foot ground contacts to a metronome beat. Post hoc analyses demonstrated that participants rocked at the desired step lengths and frequencies and that rocking half-cycles were of equal duration. Our university approved the protocol and participants gave their written informed consent prior to experimentation.

We measured the ground reaction forces, joint kinematics and metabolic cost during each rocking trial. Force plates measured the individual limb ground reaction forces and moments (Bertec Corporation, Columbus, OH) at 960 Hz and these signals were then low-pass filtered (4th order, zero-lag, 25 Hz cut-off, Butterworth filter). An 8-camera motion capture system (Vicon Motion Systems, Los Angeles, CA) recorded the kinematics of reflective markers placed bilaterally on the fifth metatarsal of the foot, the lateral malleoli, the lateral epicondyles of the knee, the greater trochanters, and on the sacrum. Marker data was captured at 120 Hz and then low-pass filtered (4th order, zero-lag, 6 Hz cut-off, Butterworth filter). We estimated metabolic power using measured oxygen consumption and carbon dioxide production (Vmax Encore, SensorMedics Corp., Yorba Linda, CA) [12,13]. To allow time for participants to reach steady state, we analyzed respiratory gases over the final three minutes, and ground reaction forces and kinematic data over the final minute, of each 6-min trial. Prior to beginning the rocking trials, we determined each participant's resting metabolic power during quiet standing and subtracted this cost from all their metabolic measurements.

2.3. Data analyses

We calculated the work performed on the COM using the individual limbs method [6]. We defined each rocking cycle as beginning when the COM reversed direction from moving backward to moving forward, and averaged the joint angular velocities, COM velocities and COM work rates across rocking cycles within each trial. The various measures of work were calculated from cumulative time-integrals of the COM work rate during each phase of the rocking cycle (e.g. forward transition). The start and end of each transition were identified from the minimum and maximum vertical COM velocities, respectively [5]. Push-off work was defined as the positive work performed by the trailing limb during the transition and collision work was defined as the negative work performed by the leading leg during the transition. To quantify the coordination of push-off and collision work, we calculated the transition work ratio n as the average of two ratios: (a) the magnitude of forward collision work as a fraction of forward push-off work, and (b) the magnitude of backward push-off work as a fraction of backward collision work. This averaging is necessary because, unlike our rocking model, human subjects are

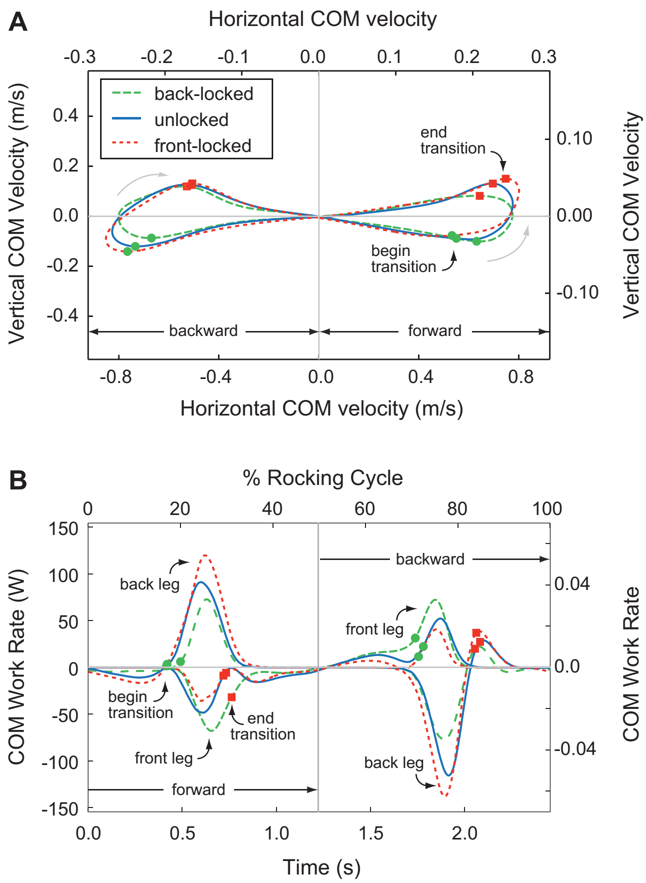

Fig. 3. (A) Hodographs illustrate the sagittal plane COM velocity components. The forward and backward transitions began when the vertical COM velocity reached a minimum and it started to be redirected upwards (green circles). The transitions ended when the vertical COM velocity reached its maximum indicating that the velocity redirection was completed (red squares). In the front-locked condition, the COM travelled faster at the end of the forward transition when compared to the beginning, but travelled slower at the end of the backward transition when compared to the beginning. The change in magnitude of the COM velocity before and after each transition was reduced in the back-locked condition. (B) COM work rate. Restricting the motion of the front leg joints decreased the push-off by the front leg during the backward transition requiring an increase in negative work by the back leg to complete the COM redirection. The back leg compensated for the decrease in positive work during the backward transition by increasing push-off during the forward transition, reducing the negative work required by the front leg to complete the COM redirection. The back-locked condition reduced the push-off by the back leg during the forward transition resulting in a similar cascade of events. The presented data is the average across all participants. The left and bottom axes are in SI units, while the right and top axes are in dimensionless units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

not required to exactly reverse their coordination of push-off and collision work during forward and backward transitions. We defined the average COM work rate as total positive COM work divided by rocking cycle duration.

We performed statistical comparisons using paired t-tests with a level of significance of $p = 0.05$. To account for differences in body size, we analyzed all variables in their dimensionless form using base units of participant mass, M, gravitational acceleration, g, and leg length, L [5,12]. We used average mass and leg length to re-dimensionalize variables and report results in SI units.

3. Results

Restricting the joint motion of a leg reduced its push-off work and increased the collision work required of the unrestricted leg in order to complete the COM velocity redirection (Figs. 3 and 4). During the forward transition, restricting the back leg reduced its push-off work by 32 ± 10% (mean ± standard deviation) and increased the front leg collision work by 40 ± 31% relative to the

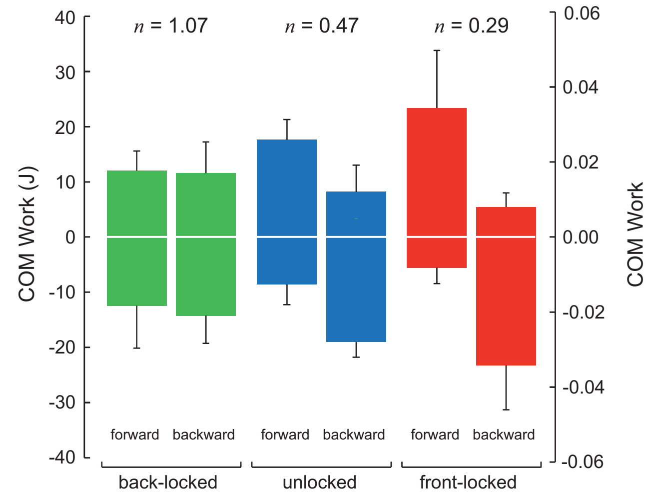

Fig. 4. Transition work. Positive values illustrate the positive COM work performed by the trailing leg during the transition (push-off work) while the negative values illustrate the negative COM work performed by the leading leg during the transition (collision work). Data for the forward and backward transitions are the bars on the left and right sides of the adjacent pairs, respectively. The heights of the bars indicate the averages, and the error bars the standard deviations, across all participants. The left axis is in SI units and the right axis is in dimensionless units.

unlocked condition ($p = 1.9 \times 10^{-5}$ and $p = 4.0 \times 10^{-3}$, respectively). During the backward transition, restricting the front leg reduced its push-off work by 24 ± 36% and increased the back leg collision work by 21 ± 33% relative to the unlocked condition ($p = 0.05$ and $p = 0.06$, respectively). Subjects compensated for the reduction in locked leg push-off work by increasing push-off work in the unrestricted leg during the subsequent transition, which reduced the collision work required to complete the COM velocity redirection relative to the unlocked condition. Restricting the back leg increased front leg push-off work by 50 ± 34% ($p = 1.9 \times 10^{-3}$) during the backward transition which decreased back leg collision work by 26 ± 18% ($p = 2.3 \times 10^{-3}$). Restricting the front leg increased back leg push-off work during the forward transition by 32 ± 47% ($p = 0.05$) which decreased front leg collision work by 28 ± 32% ($p = 0.02$).

As hypothesized, a departure from the predicted optimal coordination for step-to-step transitions, in which push-off and collision work are equal in magnitude, increased the total mechanical work required to rock. When compared to the unlocked condition, which had a transition work ratio of 0.47 ± 0.21, restricting the front leg increased the difference between

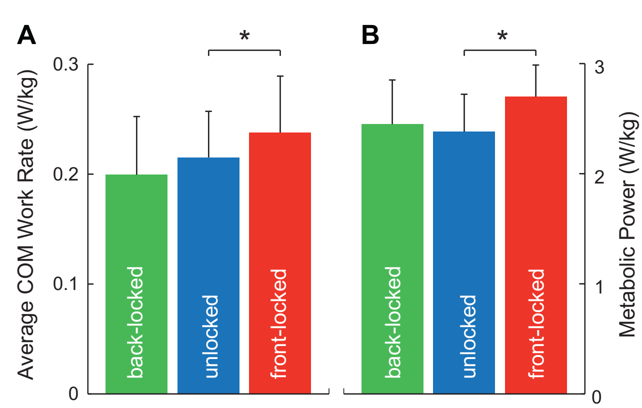

Fig. 5. Average COM work rate (A) and metabolic power (B) in the back-locked, unlocked and front-locked conditions. The heights of the bars indicate the averages, and the error bars the standard deviations, across all participants. The asterisks indicate significant differences between conditions ($p < 0.05$).

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push-off and collision work in both forward and backward transitions reducing transition work ratio to 0.29 ± 0.19 ($p = 0.05$). This shift away from the optimal coordination increased the average COM work rate by $11 \pm 11\%$ ($p = 0.02$, Fig. 5A). The increase in mechanical work came with a metabolic penalty—metabolic power increased by $15 \pm 12\%$ ($p = 5.6 \times 10^{-3}$, Fig. 5B). Restricting the back leg decreased the difference between push-off and collision work in both forward and backward transitions yielding a work ratio of 1.07 ± 0.69 ($p = 8.5 \times 10^{-3}$). This shift towards the optimal coordination resulted in a $8 \pm 12\%$ reduction in average COM work rate that is consistent with the hypothesis but short of statistical significance ($p = 0.06$). Any savings in metabolic cost due to the reduction in COM work in the back-locked condition relative to the unlocked condition appeared to be offset by a metabolic penalty for forcing subjects away from their preferred manner of rocking resulting in no change to the metabolic power required to rock ($p = 0.45$).

4. Discussion

The coordination of push-off and collision work appears to be important for determining the mechanical work required for step-to-step transitions. Forcing subjects to redirect the COM velocity with an unequal division of work between push-off and collision, accomplished by restricting the motion of the front leg joints, resulted in an increase in total mechanical work. The increase in mechanical work was modest (11%) but in line with that predicted by our simple rocking model; a decrease in transition work ratio from 0.47 to 0.29 increased the mechanical work to rock in the model by 15% at a simulated step length of 0.8 L.

Coordination patterns that minimize mechanical work do not necessarily minimize metabolic cost. In our control condition, participants preferred to rock with a transition work ratio of 0.47 performing significantly more push-off work during forward transitions than during backward transitions (Figs. 3 and 4). The mechanical work penalty for this preferred transition work ratio was not severe—mechanical work was only 8% lower in the back-locked condition in which the transition work ratio was near unity (Figs. 4 and 5). We suspect that participants preferred this manner of rocking because the forward-pointing foot allows the ankle to push off effectively during the forward transition, but little ankle joint displacement is available for pushing off when moving backward. While the knee joint could perform backward push-off work, it would necessitate that participants keep their knee bent during the previous inverted pendulum phase—a metabolically expensive strategy [14,15].

Our experiment has a number of limitations that should be taken into consideration before extrapolating our findings to healthy and pathological walking. First, our subjects preferred to rock with sub-optimal transitions which differs considerably from healthy walking where the work to redirect the COM velocity is partitioned more equally between the trailing and leading legs [6]. Consequently, restricting the back leg in walking to reduce its push-off work would likely effect walking in a manner more similar to what we found for the front-locked condition than the back-locked condition—more required collision work, a less optimal transition work ratio, more total mechanical work and an increase in metabolic cost. Second, the COM in rocking does not continuously progress forward as in walking, but reverses directions twice for each rocking cycle. As a result, the COM velocity at the beginning of each transition is lower in rocking than walking when comparing the two at the same step length and frequency, thus requiring less work to redirect the COM velocity. In terms of mechanical work, rocking in our control condition was roughly equivalent to a slow walk—the average COM work rate during rocking was 0.22 ± 0.04 W/kg while walking at 0.75 m/s has an average COM work rate of 0.28 ± 0.01 W/kg [6,7]. At faster walking speeds, we anticipate larger effects of immobilization; the required push-off work increases strongly with speed due to increases in both the COM velocity and the angle over which it must be redirected [5,7]. A third limitation is that our method of restricting the ankle and knee joints did not entirely eliminate the contribution of the trailing leg to redirecting the COM velocity. This was due to three factors: (a) the locked braces still underwent some angular displacement (Fig. 2), (b) subjects reported that the body retained some ability to move within the brace itself, and (c) the curved shape of the brace rocker bottom helped passively redirect the COM velocity [16]. While it may have been desirable to use conditions that simulated faster walking, as well as further restricting the ability of our subjects to push-off, we nevertheless feel that our current experimental paradigm was effective at testing our predictions.

The effect of coordinated transition work on total mechanical work may have direct implications for understanding pathological gait. Two general characteristics of gait pathology, irrespective of etiology, are the reduction in coordination and strength of one or both legs and the increase in the metabolic cost required to walk. In persons with stroke, for example, mechanical work measurements suggest that the paretic leg performs less push-off work and that the metabolic cost of walking is elevated [17,18]. Similarly, amputees expend more energy to walk at the same speed as individuals with both limbs intact, and the energetic penalty increases with the degree of amputation [2]. Houdijk and colleagues have found an association between the coordination of step-to-step transitions and metabolic cost in amputees and subjects with total ankle arthroplasty [19,20]. This also appears to be the case in children with cerebral palsy who, when compared to healthy children, exhibit a large reduction in push-off work and large increases in both collision and total mechanical work, helping to explain their elevated metabolic cost [21,22].

The optimal transition hypothesis may help guide designs of rehabilitation strategies and assistive devices aimed at lowering metabolic cost and increasing patient mobility. For assistive devices, Collins and Kuo have already begun this effort using a computer-controlled artificial foot to replace push-off work in intact subjects with an artificially impaired ankle [23]. Perhaps the metabolic cost of walking after stroke or spinal cord injury could be lowered by electrically stimulating the paretic leg extensors to assist push-off in a manner similar to that currently used to correct drop foot [24]. For rehabilitation strategies, the energetics of step-to-step transitions indicate that training should target not only the strength of paretic leg extensor muscles but also their ability to perform mechanical power with the appropriate timing. The physics suggests that for those who can not push-off at all, small improvements can make a big difference in step-to-step transition work and metabolic cost, perhaps allowing those patients to walk further and faster.

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Conflict of interest

None.

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