

Metabolic and Mechanical Energy Costs of Reducing Vertical Center of Mass Movement During Gait

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Objectives: To test the hypothesis that reducing vertical center of mass (COM) displacement will lower the metabolic cost of human walking. To examine changes in joint work associated with increasing and decreasing vertical COM movement during gait.

Design: Randomized repeated measures.

Setting: Human Neuromechanics Laboratory, University of Michigan.

Participants: Able-bodied subjects (N=10).

Interventions: Subjects walked at 1.2m/s on a treadmill and overground. Subjects manipulated vertical COM displacement either by adjusting stride length or by using visual feedback to reduce COM movement.

Main Outcome Measures: We measured kinematic and kinetic data to calculate vertical and lateral COM displacements, joint torques, and work. In addition, we collected oxygen consumption to calculate metabolic power.

Results: Increasing and decreasing vertical COM displacement beyond subjects' preferred range resulted in increases in the metabolic cost of walking. When vertical COM displacement was reduced, corresponding increases in positive ankle and hip work and negative knee work were observed.

Conclusions: Humans are capable of walking in a manner that will reduce COM displacement from normal. Decreasing vertical COM movement results in increases in metabolic energy costs because of greater mechanical work performed at the hip, knee, and ankle joints. Thus, reducing vertical COM movement is not a successful strategy for improving either metabolic or mechanical energy economy during normal walking by able-bodied subjects.

Key Words: Biomechanics; Efficiency; Rehabilitation; Walking.

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SCIENTISTS HAVE DEBATED the energetic cost associated with body COM movement during gait for over 50 years.¹⁻⁴ The COM rises in each step as humans "vault" over a single extended support limb (fig 1). Metabolic energy expenditure would be expected if muscular work is needed to raise

the COM each step. One might then conclude that the metabolic energy requirements of gait could be reduced by actively decreasing or minimizing vertical COM movement. However, recent studies^{5,6} show that humans do not minimize vertical COM displacement during gait and that reducing it can actually increase metabolic energy expenditure. Human gait is likely the result of optimizing many variables (ie, speed, stride length, stride rate, step width) that influence metabolic efficiency,⁷⁻¹⁴ making it unclear why decreased vertical motion of the COM should result in greater energy expenditure. The purpose of this article was to examine the mechanics and metabolic requirements associated with reduced vertical COM movement during gait.

In 1953, Saunders et al¹ published a highly influential article and hypothesized that humans walk with an energetically optimal gait pattern and that "an overall displacement of the center of gravity of the body through a sinusoidal path of low amplitude . . . requires the minimal expenditure of energy."^{1(p554)} They also stated that "the energy expended during walking at a constant cadence is divided approximately equally between the production of rhythmic oscillations of the legs and elevation and depression of the center of gravity of the body."^{1(p553)} Supporting experimental data were not presented, but at least a dozen textbooks¹⁵⁻²⁹ have interpreted this work to mean that it is desirable to minimize or reduce COM motion during walking. For example, Perry³⁰ states that "minimizing the amount that the body's center of gravity is displaced from the line of progression is the major mechanism for reducing the muscular effort of walking, and consequently, saving energy."^{30(p40)} Several recent studies³¹⁻³⁵ have experimentally tested 3 of the 6 kinematic determinants originally hypothesized and found that they did not substantially reduce COM motion. Some textbooks have subsequently been updated to acknowledge this issue,^{36,37} but the 6 determinants of gait are still well accepted in some fields.³³

Two studies have experimentally manipulated COM movement to test for an energetic cost to displacement of the COM.^{5,6} In both studies, subjects used visual feedback to decrease their normal vertical COM movement during walking. This reduction resulted in at least a 50% increase in metabolic energy cost. Both studies found that the mechanical work performed on the COM by the combined limbs was unaffected, suggesting that the increase in cost was because of force production or inefficiencies in muscle usage. Theoretic analysis, however, indicates that a level COM trajectory can increase the work performed at the joints,³⁸ even if muscle efficiency remains unchanged. The actual cause of the increased energetic

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List of Abbreviations

ANOVA	analysis of variance
COM	center of mass
PSL	preferred stride length
VFB	visual feedback
$\dot{V}O_2$	oxygen consumption

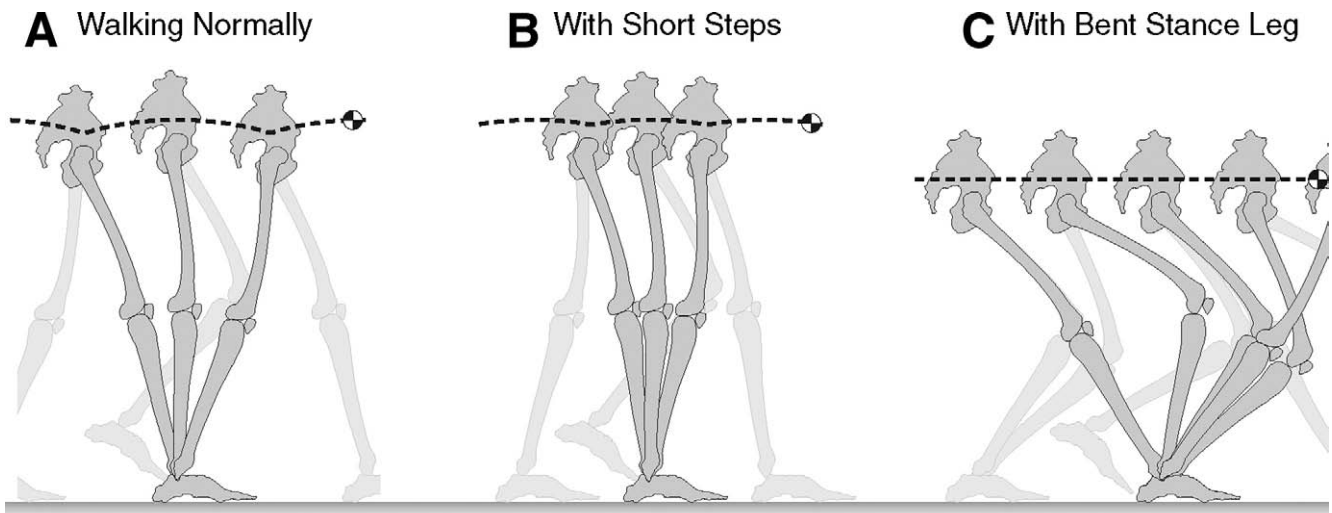


Fig 1. Methods for decreasing vertical COM displacement. Compared with (A) normal walking, COM displacement may be reduced by (B) taking shorter strides or by (C) walking with a flexed leg during the single stance phase. Shorter strides require faster cadence to walk at the same speed, with a potential consequence of an increased torque and work for moving the legs back and forth relative to the body. A flexed leg may also require greater knee extension torque to support body weight, resulting in increased work at that joint. Both of these could potentially have energetic costs that outweigh the hypothesized cost of displacing the COM.

cost remains unknown because studies to date have not measured the work performed by the joints when COM displacement is reduced.

The purpose of this study was to directly test the hypothesis that minimizing vertical COM displacement decreases metabolic cost during human walking and to examine the underlying mechanical effects at the joint level. We tested 2 cases in which COM displacement could be manipulated without changing walking speed. First, subjects walked at a constant speed but with varying stride length and frequency combinations (see fig 1). This was designed to reduce vertical COM movement, with additional effects on the hypothesized rhythmic oscillations component of energy expenditure.^{1,11} Second, subjects walked at a constant speed and stride length but attempted to reduce their vertical COM motion by using visual feedback of their sacrum position (see fig 1). This was similar to previous studies,^{5,6} but here stride length and frequency were held constant to control for the rhythmic oscillations component. Our study tests both methods of reducing vertical COM displacement with regard to energy expenditure and examines the mechanical torque and power demands from the joints.

METHODS

We examined COM displacement, metabolic energy cost, and mechanical work performed at each joint during normal walking by able-bodied subjects. Vertical COM displacement was experimentally manipulated, first with visual feedback and second by control of stride length, and then compared against energy expenditure. We also performed inverse dynamic calculations to determine the work performed at each joint and the means by which subjects accomplished smooth walking.

Subjects

Ten subjects (5 male and 5 female subjects; mean age \pm SD, 27 ± 4 y) signed informed consent forms approved by the University of Michigan Health Sciences Institutional Review Board and participated in this study. All subjects were considered to be nonpathologic ambulators in good health. All data

were collected at the University of Michigan, Human Neuro-mechanics Laboratory.

Experimental Design

We collected kinematic, kinetic, and metabolic data during 5 treadmill walking conditions and 1 standing trial for all 10 subjects. The conditions included walking at 4 different stride length and frequency combinations and walking while receiving VFB about sacral position, all at a speed of 1.2m/s. The stride lengths were 0.6, 0.8, 1.0, and 1.2 as a fraction of PSL, with stride frequency changing inversely because of the fixed speed. In the VFB condition, subjects were asked to use the feedback to try and minimize vertical COM displacement while walking at 1.0 PSL. We also collected mechanics (kinematic and kinetic) data from 6 of the subjects during overground walking.

Metabolic Rate Measurements

During all treadmill walking and standing conditions, we measured the rate of $\dot{V}O_2$ using an open-circuit respirometry system^a. We collected data for continuous 7-minute periods. For all trials, the first 3 minutes were used to allow the subjects to reach steady state. We used the subsequent 3 minutes to calculate average $\dot{V}O_2$ (mL O_2 /s) values. We discarded the last minute of data because of a delay between breath expiration and breath analysis. We calculated metabolic power (W) for each trial by using the standard relation³⁹ of 20.96W for 1mL O_2 /s. We subtracted the metabolic power for standing from all walking values to derive the subjects' net metabolic power (W). Net metabolic power was normalized by subjects' body mass (kg). It was also converted to cost of transport by dividing power by the product of body weight (N) and walking speed (m/s). Respiratory exchange ratios were less than 1 for all subjects and conditions, indicating that energy was supplied primarily by oxidative metabolism in all test conditions. No metabolic data were collected during overground walking.

Kinematic Measurements

We collected 3-dimensional kinematic data by using a 6-camera system^b for all treadmill (240Hz) and overground (120Hz) walking conditions. During treadmill walking, we collected 2 minutes of continuous kinematic data that coincided with the time period during which metabolic data were collected for steady-state walking. For overground walking, we collected 10 trials of 2 complete stride cycles for each condition. Different kinematic marker placements were used during treadmill and overground walking. During treadmill walking, the kinematic data were used to calculate COM position. Therefore, we used a full body marker set for treadmill walking, with 28 markers placed bilaterally on the subject. Locations of the markers were on the fifth metatarsal of the foot, the heel, the medial and lateral malleoli, on wands extending laterally from the shank and thigh segments, the medial and lateral epicondyles of the knee, the greater trochanter, the anterior superior iliac spine, the sacrum at the midpoint between the posterior superior iliac spinae, the tip of the acromion process, cervical vertebra 7, the lateral epicondyle of the humerus, and at the midpoint of the wrist between the styloid processes. During overground walking, kinematic data were used only to calculate lower-body joint angles and perform inverse dynamic calculations. Therefore, we used only a lower-body marker set for overground walking, with 29 markers placed bilaterally on the pelvis and lower limbs by using a cluster marker set. Locations of the markers were on the fifth metatarsal of the foot, the heel, the medial and lateral malleoli, the medial and lateral epicondyles of the knee, the greater trochanter, the anterior superior iliac spine, the sacrum, and in 3 marker clusters placed on the thigh and shank.

Kinetic Measurement

During treadmill walking, we recorded net ground reaction force data from 2 force plates^c that completely supported the treadmill. We collected force plate data during a continuous 2-minute period synchronized with the period during which kinematic data were recorded. During overground walking, the 2 force plates were positioned to record ground reaction force data during 2 consecutive steps. All force plate data were sampled at 1200Hz.

Protocol

All 10 subjects performed the treadmill walking portion of the experiment. First, we determined the PSL for each subject while walking at 1.2m/s. Subjects were given 3 minutes to become accustomed to walking on the treadmill. After accommodation, the subjects' average preferred stride frequency (stride cycles per second) was determined from the time required to complete 60 stride cycles. We calculated the stride frequencies that corresponded with stride lengths of 0.6, 0.8, 1.0, and 1.2 PSL.

Next, we recorded metabolic, kinematic, and kinetic data from the subject during 7 minutes of quiet standing. This was followed by 5 walking trials (stride lengths of 0.6, 0.8, 1.0, and 1.2 PSL and 1.0 PSL while using visual feedback to try to minimize vertical COM displacement). All walking was performed on a treadmill at a velocity of 1.2m/s. The order of the walking conditions was randomized between subjects. Subjects were given rest periods of up to 3 minutes between trials. During all walking trials, the subjects adjusted their heel strikes to match a metronome that was set to the specific stride frequency needed to produce the target stride length. These experiments were performed on a treadmill both to easily

control for speed and to allow subjects to reach steady state for metabolic recordings.

During the visual feedback conditions, the equipment was arranged to provide subjects with position information about the movement of their sacrum during walking. We displayed in real-time the vertical and lateral position of the subjects' sacral kinematic marker projected and amplified by a factor of approximately 10 on a white board. Horizontal lines marked every 0.1m allowed subjects to easily determine vertical changes in their sacral position. The board was positioned 3.0m in front of the subject. Subjects were instructed to try and minimize vertical movements of their sacrum during walking. During the visual feedback condition, subjects walked at the same stride length as their previously determined PSL by keeping step frequency matched to a metronome. Stride length, known to effect metabolic cost, was matched to PSL to ensure that differences between the 2 conditions were caused by the COM displacement as opposed to stride length. Although not given specific instructions on how to minimize vertical COM movements, all subjects choose to walk using a bent knee (Groucho) style. Subjects were given 2 minutes to practice using visual feedback to minimize COM movement before recording this trial.

Six of the subjects (3 male, 3 female) performed the overground walking portion of the experiment. We did not collect overground data on the other 4 subjects because the mechanics data exhibited little variability. During the overground testing, subjects repeated all of the conditions (standing plus 5 walking conditions) performed during the treadmill testing. Repeating the conditions overground instead of on the treadmill was necessary for collecting data needed to perform inverse dynamics calculations. During overground walking trials, subjects walked straight across a 7.6-m walkway. Force plates were positioned in the walkway to capture 2 consecutive heel strikes (left and then right). We determined overground walking speed by using a timer connected to 2 light triggers. The light triggers were placed a distance of 2.5m apart. The triggers were situated to capture the time during which the subjects crossed the 2 force plates. Subjects were required to walk at an average speed of 1.2m/s. Only trials performed within 5% of the target speed were accepted. Heel strikes during overground walking were matched to a metronome to ensure that the subject walked at the target stride lengths. Subjects performed 10 successful (target speed and stride length) overground walking trials for each condition.

Analysis

We calculated COM displacement by using 3 methods: a single sacral marker, segmental analysis, and force plate analysis. The sacral marker served as a rough estimate of COM displacement used during the visual feedback condition. The other 2 methods were computed because they take into account motions of the limbs relative to the pelvis, which significantly affects COM position.³⁶ For the segmental method, we smoothed marker data and used this to calculate joint centers and segmental COMs. For each subject's data, the total body COM was determined for each frame of kinematic data by calculating the vertical positions of the COMs of each body segment and then using a weighted average based on the segment mass fractions to calculate total body COM position. The force plate method was similar to that used by the previous studies^{5,6} in which ground reaction forces were used to yield COM acceleration, which was then integrated twice to yield COM displacement.⁴⁰ These methods are described in detail and compared quantitatively in an earlier publication.⁴¹ The peak-to-peak amplitudes of the resulting vertical displacement

Table 1: Mean and SD of Vertical COM Displacement and Net Metabolic Power for 10 Subjects During Treadmill Walking and Ankle, Knee, and Hip Work During Overground Walking for 6 Subjects

Condition	Energy Expenditure (Cost of Transport)	Vertical COM Displacement (% L)	Lateral COM Displacement (% L)	Ankle Work Per Stride (J)	Knee Work Per Stride (J)	Hip Work Per Stride (J)
0.6 PSL	0.47±0.10*	1.60±0.56*	1.08±0.27*	2.66±2.44*	-8.63±2.56*	8.18±2.45*
0.8 PSL	0.29±0.05*	2.85±0.67*	1.83±0.47*	1.00±1.45*	-6.07±2.18*	5.62±1.38*
1.0 PSL	0.22±0.03	3.82±0.52	3.31±0.44	-0.10±1.00*	-3.32±1.28*	3.87±1.26*
1.2 PSL	0.30±0.04*	4.75±0.76*	4.37±0.40*	0.41±0.77*	-2.39±1.04*	2.72±1.35*
VFB	0.52±0.11*	1.58±0.55*	3.74±0.40	2.43±1.58*	-8.57±2.88*	4.48±2.34
ANOVA	7.4E-13	3.6E-12	2.5E-7	0.022	9.3E-04	0.0015

NOTE. All measures were significantly different across conditions (ANOVA, *P* shown in bottom row).

*Significant differences between the 1.0 PSL condition and the other 4 walking conditions in post hoc multiple comparison tests (*P*<.05).

waveforms were averaged over a continuous 20-second period (segmental method) or 120-second period (force plate method) for each trial to calculate the vertical displacement of the COM. Vertical displacement waveforms of the smoothed sacral marker data were averaged over a continuous 20-second period for each trial. Lateral COM displacement was evaluated in a similar manner.

Commercially available gait analysis software^d was used to calculate bilateral hip, knee, and ankle joint angles, torques, work, and powers for each of the overground walking trials. Stride cycles were normalized to percent gait cycle and averaged for each subject.

All COM displacements were normalized to leg length. A repeated-measure ANOVA was performed for each of the treadmill walking conditions to check for differences in normalized vertical COM displacement between the 3 different estimation methods (sacral marker, segmental analysis, and force plate method). We set the significance level at α equals .05 and used a post hoc Holm-Sidak multiple comparison test to detect significant differences where appropriate, with a family-wise error rate of α equals .05. In addition, we ran two 1-way, repeated-measure ANOVAs to check for differences in normalized vertical COM displacement and energetic cost of transport between the 4 stride-length walking conditions. Again, we set the significance level at α equals .05 and used a post hoc Holm-Sidak test to check for differences where appropriate. We ran 2 repeated measure *t* tests to check for differences in vertical COM displacement and cost of transport between normal walking and the visual feedback conditions. The significance level was set at *P* less than .05. Finally, we ran three 1-way repeated-measure ANOVAs to check for differences in positive ankle work, negative knee work, and positive hip work between conditions with a significance level of α equals .05. Again, post hoc multiple comparisons were performed as needed to check for differences between conditions. We used either JMP statistical software^e or MATLAB Statistics Toolbox^f to perform all statistical analyses.

RESULTS

Center of Mass Displacement

There was no difference between the force plate and segmental analysis methods for calculating vertical COM displacement at any of the 5 walking conditions (Holm-Sidak multiple comparison, *P*>.05). The single sacral marker method of calculating vertical COM displacement was different from the other 2 estimation methods during the 0.6, 1.0, and 1.2 PSL conditions (Holm-Sidak multiple comparison, *P*<.05). However, for the VFB condition, during which subjects used VFB about the sacral marker position to minimize COM movement,

we found no difference between any of the 3 methods used to estimate COM position (Holm-Sidak multiple comparison, *P*>.05). Because there was no difference between the force plate and segmental analysis methods, all COM data reported are from the force plate analysis because it was calculated over a longer 120-second time period rather than the 20-second period used for the segmental analysis. The vertical displacement was 33.7±4.7mm during the 1.0 PSL condition, serving as the baseline for all comparisons.

Altering stride length resulted in significant changes in vertical COM displacement during walking (ANOVA, *P*=3.6E-12) (table 1 and figs 2, 3A). Post hoc tests revealed that vertical COM displacement for all conditions was different from the 1.0 PSL walking condition (Holm-Sidak multiple comparison, *P*<.05). When subjects walked with stride lengths larger than normal (1.2 PSL), vertical COM displacement increased by

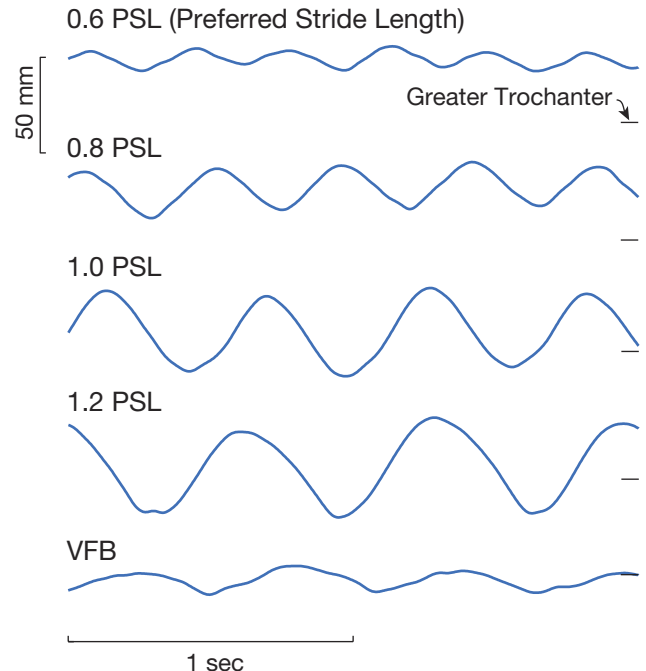


Fig 2. A representative vertical COM trajectory from a single subject. The trajectories are shown for different stride lengths, shown as a fraction of PSL, and for a VFB condition in which subjects consciously attempted to reduce vertical COM displacement based on a projected image of their COM height. Data shown are for 2 seconds of treadmill walking. The COM height is shown relative to the greater trochanter during standing.

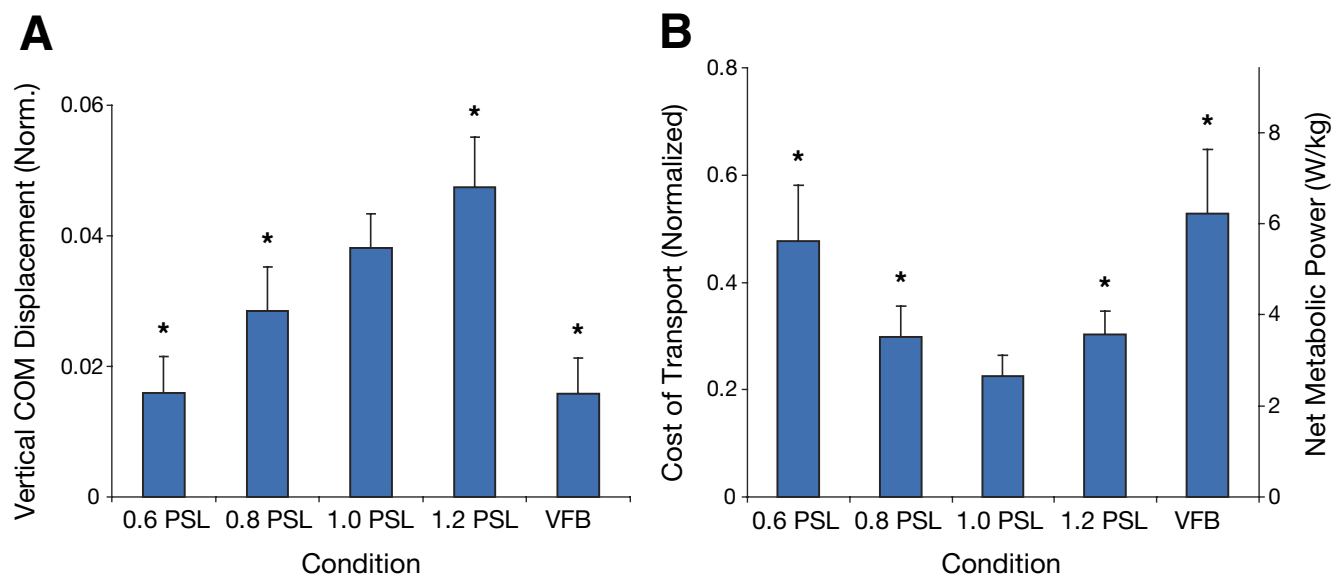


Fig 3. (A) Vertical COM displacement and (B) metabolic energy expenditure during treadmill walking as a function of walking condition. Data shown are mean \pm SD denoted by error bars. In A, displacements were calculated for the 5 conditions for all subjects and displayed normalized by subjects' leg length (*L*). In B, energy cost was calculated for the 5 conditions from all subjects and displayed in terms of a dimensionless cost of transport and net metabolic power (left and right axes, respectively). *Conditions significantly different from the 1.0 PSL normal walking condition ($P < .05$).

24% from the 1.0 PSL condition. In contrast, when stride lengths were shortened to 0.8 and 0.6 PSL, vertical COM displacement decreased significantly by 25% and 58%, respectively.

Subjects were also able to use VFB to significantly reduce vertical COM displacement during walking compared with normal, 1.0 PSL, walking (repeated-measure *t* test, $P = 1.36E-6$). During the VFB condition, subjects were able to reduce vertical COM displacement by 59% from that occurring during the 1.0 PSL condition (see table 1 and figs 2, 3A).

Lateral COM displacement changed in rough concordance with stride length. As with vertical displacement, it increased with stride length (range, 9.62–38.6mm) across these conditions. Lateral COM displacement did not vary significantly between the VFB condition and normal walking at PSL ($P > .05$) (see table 1).

Metabolic Energy Cost

Altering stride length resulted in significant changes in the energetic cost of transport during walking (ANOVA, $P = 7.45E-13$) (see table 1 and fig 3B). Post hoc tests revealed that normalized metabolic power for all conditions was greater than the 1.0 PSL condition (Holm-Sidak multiple comparison, $P < .05$). All changes in stride length from preferred stride length resulted in an increase in energy expenditure. Metabolic power was least for the 1.0 PSL, at 2.6 ± 0.5 W/kg. When stride length was increased to 1.2 PSL, metabolic power increased by 36%. When stride length was decreased to 0.8 and 0.6 PSL, metabolic power increased 32% and 114%, respectively. In addition, when subjects used VFB to reduce their vertical COM displacement, there was an increase in metabolic power (repeated measure *t* test, $P = 1.11E-5$). During the VFB condition, subjects showed the greatest metabolic power between all 5 walking conditions, 136% above normal (see table 1 and fig 3B).

Metabolic cost was least for the 1.0 PSL condition, although this was not the condition in which the COM vertical displacement was least. Subjects had the smallest vertical COM dis-

placements during the 0.6 PSL and VFB conditions. However, these were the conditions in which metabolic cost was the greatest (fig 4).

Mechanics

When subjects walked with reduced stride length, they changed their joint kinematics and kinetics. Subjects decreased their hip range of motion and increased knee flexion during the stance phase when they walked with shorter strides (fig 5). This

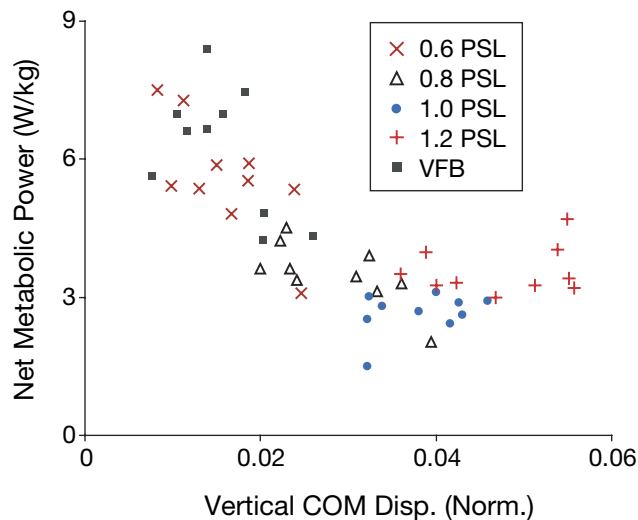


Fig 4. Metabolic energy expenditure versus individual vertical COM displacement for all subjects. The mean metabolic rate and mean COM displacement are shown for each subject. Energy expenditure rate increased for vertical COM displacements below that of the 1.0 PSL normal walking condition. Abbreviations: Disp, displacement; Norm, normal.

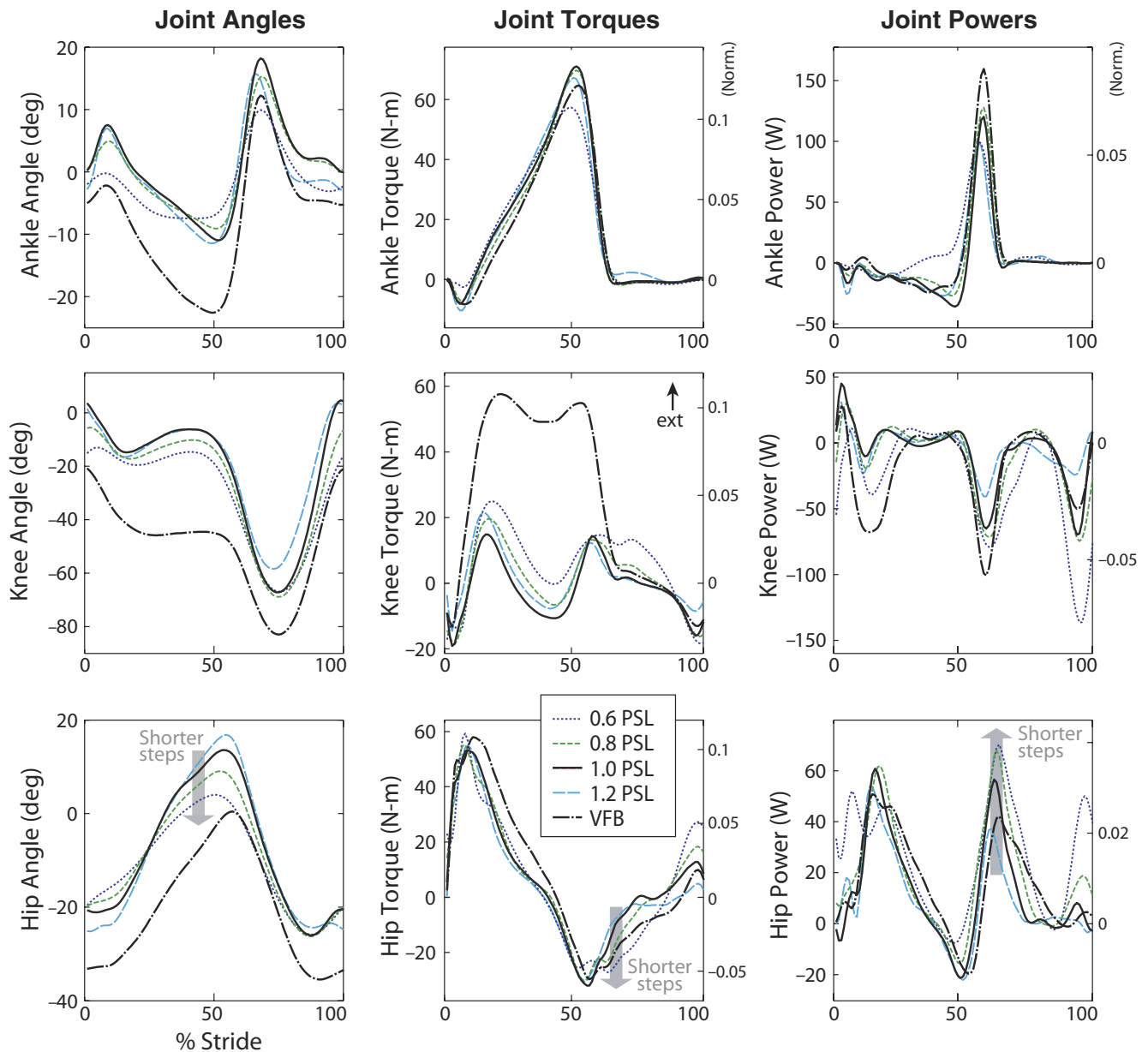


Fig 5. Mean hip, knee, and ankle joint angle (left column), joint torque (middle column), and joint powers (right column). Data were calculated during overground walking for all conditions from 6 subjects. Abbreviation: deg, degrees.

resulted in greater work and positive peak power performed at the hip and increased negative work and peak power performed at the knee (see table 1 and figs 5, 6). The positive hip joint work performed per stride increased by 5.5J from the 1.2 PSL to 0.6 PSL conditions. Similarly, negative work performed at the knee increased in magnitude by 6.2J over the same conditions. Decreasing stride length also resulted in an increase in work performed at the ankle during the 0.8 and 0.6 PSL conditions (see table 1 and fig 6). Subjects were able to use VFB to decrease vertical COM displacement by adopting a “Groucho” gait style⁴² consisting of walking with a very flexed knee during stance phase (see fig 5). Walking in this manner resulted in a large increase in ankle and knee torques and work produced during stance phase, most substantially a significant 158% increase in the magnitude of negative work performed at

the knee per stride (see figs 5, 6). Post hoc tests revealed that ankle, knee, and hip work were significantly different from preferred walking (1.0) for all 4 other conditions tested (Holm-Sidak multiple comparison, $P < .05$) with the 1 exception of hip work during the VFB condition. Peak knee torque was 2.4 times higher ($P = .001$) in the VFB condition than in preferred walking. Although only 6 subjects were used during the overground walking trials, power analysis revealed statistical power values greater than 0.9 for all variables examined during these trials.

DISCUSSION

We sought to test whether reducing the vertical displacement of the COM improves walking economy in able-bodied subjects. Our results show that reduced COM displacement is not

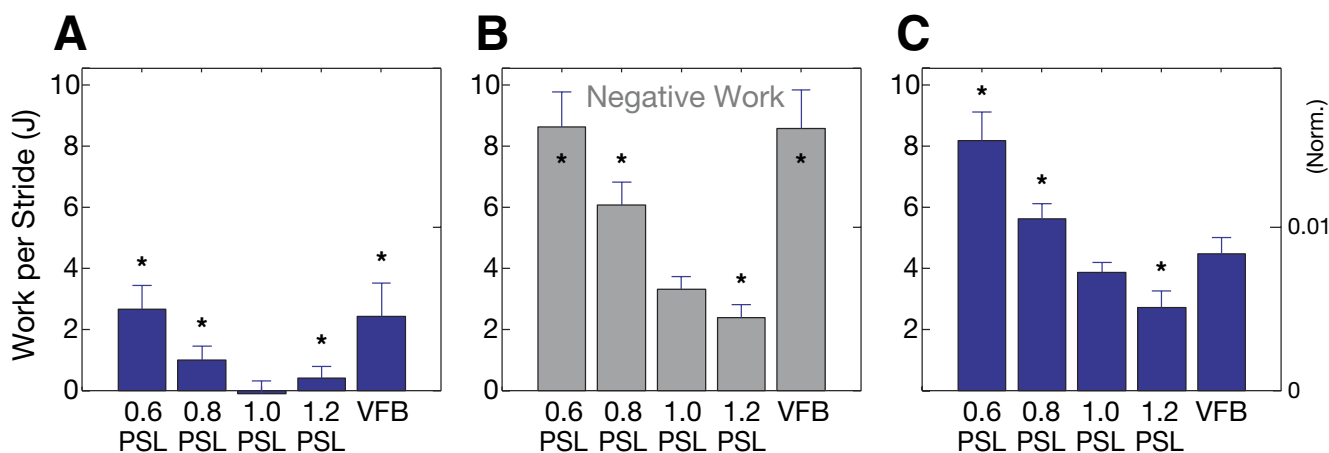


Fig 6. Mean and SD of total work per stride for (A) ankle, (B) knee, and (C) hip joints. Knee work is negative. Work was calculated during overground walking for all conditions from 6 subjects. *Conditions significantly different from the 1.0 preferred walking condition ($P < .05$).

advantageous for either metabolic energy economy or the reduction of mechanical work at the joints. Energy expenditure increased whether subjects walked with shorter strides or by using VFB to reduce COM motion. The latter results agree with previous reports,^{5,6} which are augmented here by the analysis of joint mechanics for both types of conditions.

When subjects were given VFB, they adopted a flexed-knee gait pattern to reduce their COM displacement. This required much higher single-support knee extensor torques compared with normal walking (see fig 5, peak 2.4 times higher). Winter⁴³ reported that the mechanical work performed during walking increases with greater knee flexion during stance. We similarly found that negative work performed at the knee increased by approximately 260% (see fig 6) when subjects walked with a flexed stance limb compared with their normal stance limb kinematics. This was offset by an equal amount of positive work distributed about other joints and other periods in the stride because no net work is performed over an entire stride when walking on the level.³⁸ Some of the increased positive work during VFB may be observed at the ankle before and during push-off ($\approx 40\%$ – 60% of stride) and at the hip during midstance and midswing (see fig 5). The positive work appears to be distributed such that differences might not be readily apparent in summary measures such as the work performed on the COM by the combined legs^{5,6} because some of the positive work at 1 joint may be cancelled by simultaneous negative work at another joint or the other leg.¹¹ Negative work and high extensor torques about the knee, nevertheless, show much greater mechanical demands for the bent-knee gait.

The reduction of COM displacement through VFB also led to much higher metabolic cost. Alexander⁴ identified a relatively straight knee during stance as an important mechanism for minimizing the metabolic cost of gait by decreasing moments about the knee. A straight knee also allows the leg to behave like an inverted pendulum, which allows the COM to undergo vertical displacement without necessarily requiring work. The disadvantage of flexing the knee is indicated by the peak knee torques we observed, which more than doubled in the VFB condition. High torques would be expected to cost metabolic energy even if no additional mechanical work were performed. The increased work we observed, however, was sufficient to explain much of the increased energetic cost without necessarily requiring a reduction in efficiency.⁶ Saunders et al¹ originally hypothesized knee flexion during stance as

1 of 6 kinematic methods that humans use to minimize vertical COM movement and ultimately reduce metabolic cost, but Gard and Childress⁴⁴ showed that the knee flexion of normal walking actually contributes negligibly to reducing COM displacement. Our results show that abnormally high knee flexion can significantly reduce COM displacement but at a very high energetic cost.

In this study, subjects also increased their metabolic cost when they reduced their vertical COM movement by taking shorter strides. To maintain constant walking speed, subjects had to increase their stride frequency and thus increase the effort to move their legs more quickly. In our study, subjects increased work and torque performed about the hip by approximately 210% when walking with the shortest stride length compared with their normal stride length. They also performed this work more often because higher stride frequencies were required to maintain the same walking speed. Previous studies^{45,46} have shown that fast leg motion requires greater torque and work, particularly at the hip, with high metabolic cost. Humans have an optimal stride frequency during walking,^{8,9} and increasing stride frequency requires faster leg motion in agreement with the Saunders et al¹ hypothesis regarding an energetic cost for rhythmic oscillations of the legs.

Subjects also expended more metabolic energy when they walked with greater stride length than their preferred stride length. Previous work has shown that as stride length increases, metabolic energy expenditure and mechanical work performed on the COM also increase.¹¹ This is not caused by COM displacement per se but rather by the additional negative work performed to redirect the COM velocity during step-to-step transitions and by positive work to restore the energy lost.^{11,47} The COM velocity varies during each single-support phase, with acceleration in all directions, but these accelerations appear to be driven largely by pendulum dynamics and therefore with relatively little active effort.^{4,7} The step-to-step transition refers to redirection of the COM velocity from a downward direction at the end of 1 pendulum-like single-support phase to an upward direction at the beginning of the next, with negative work performed by the leading limb and positive work by the trailing limb.³⁸ Indeed, subjects in the current study showed a significant increase in positive ankle work for push-off when they increased stride length, as would be expected for higher step-to-step transition costs.^{11,38}

Study Limitations

There are potential limitations to this study. One is that COM displacement was not truly minimized because it was controlled imperfectly and indirectly through stride length specification or by visual feedback. Therefore, subjects walked with nonzero vertical and lateral COM displacement. Nevertheless, both stride length and VFB conditions successfully reduced vertical COM displacement and resulted in large increases in energy expenditure. Simple calculations also suggest that it would still be costly to reduce COM displacement further by adopting a perfectly level trajectory, costing at least double the normal energy expenditure.³⁸

Another limitation was the relatively brief experience that subjects had with all nonpreferred walking styles. Our subjects were given at least 3 to 5 minutes of practice to accommodate to each treadmill condition, and this may not have been sufficient for them to adopt the most economic gait pattern for each case. Ortega and Farley⁵ gave subjects several times as much practice (20min) but also observed similar increases in energy expenditure. Although more extensive practice could potentially have resulted in some decrease in energy expenditure, it also appears unlikely to explain the more than doubling of cost we observed in the conditions with least COM displacement.

CONCLUSIONS

The data reported here and elsewhere^{5,6} do not support the hypothesis that it is energetically optimal to reduce COM displacement. Other studies³¹⁻³⁵ also question whether several of the determinants actually contribute significantly to reducing COM displacement. Our data do indicate that substantial energy is expended for "production of rhythmic oscillations of the legs,"^{1(p553)} but there is little evidence that it is "divided approximately equally" with other costs. This study contributes to a growing body of evidence indicating that factors other than COM displacement dominate the energetic cost of normal walking.

Clinicians and gait researchers have often used vertical COM displacement as a simple tool to predict the metabolic and mechanical energy cost of walking. The underlying theory was that reducing COM movement will minimize both metabolic and mechanical energy cost. Results from this study and others^{5,6} show the shortcomings of this assumption. Although increasing vertical COM displacement during walking will result in increased metabolic cost, it is not the COM displacement itself that is costing energy. In this study, we have shown several factors that directly affect mechanical and metabolic energy cost. These factors include producing muscle force without performing work (ie, walking with bent legs), moving the limbs relative to the COM (ie, leg swing) and step-to-step transition costs (ie, redirecting COM velocity between steps).

Clearly, there are metabolic consequences of forcibly perturbing vertical COM displacement during gait. This study, when referenced into the ever-growing body of work examining the energetics of walking, suggests that there may be an optimal (not minimum) vertical COM trajectory during walking. More importantly, it should be acknowledged that COM movement is a consequence of many factors that humans use to minimize metabolic and mechanical energy costs rather than viewing COM displacement as a cost into and of itself.

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