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Gait modification when decreasing double support percentage

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ABSTRACT

Much is still unknown about walking stability, including which aspects of gait contribute to higher stability. Walking stability appears to be related to walking speed, although the exact relationship is unclear. As walking speed decreases, the double support (DS) period of gait increases both in time and as a percentage of the gait cycle. Because humans have more control over their center of mass movement during DS, increasing DS duration may alter stability. This study examined how human gait is affected by changing DS percentage independent of walking speed. Sixteen young, healthy adults walked on a treadmill at a single speed for six one-minute trials. These trials included normal gait as well as longer- and shorter-than-normal DS percentage gaits. Subjects were consistently able to decrease DS percentage but had difficulty increasing DS percentage. In some cases, subjects altered their cadence when changing DS percentage, particularly when attempting to increase DS percentage. The changes to gait when decreasing DS percentage were similar to changes when increasing walking speed but occurred mainly during the swing period. These changes include increased hip and knee flexion during the swing period, increased swing foot height, and larger magnitude peaks in ground reaction forces. The changes in gait when attempting to increase DS percentage trended toward changes when decreasing walking speed. Altering DS percentage induced gait changes that were similar to, yet clearly distinct from, gait changes due to walking speed. Further, the difficulty of increasing DS percentage when walking at a constant speed suggests that people walk more slowly when they want to increase time spent in DS.
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1. Introduction

It is not entirely clear what factors of gait most affect stability in bipedal walking. It may be walking speed, variability, double support (DS) period, some combination of these, or some other factor (s), such as the center of pressure with respect to the center of mass. Decreased speed in the elderly is often an indicator of reduced walking ability leading to an increased risk of falling and has been associated with lower overall health (Studenski et al., 2011; Fritz and Lusardi, 2009). However, increasing speed by itself does not always improve walking ability and reduce the likelihood of falls (Bergland et al., 2003; van den Bogert et al., 2002; Pavol et al., 1999). On the other hand, slower walking has higher local dynamic stability (a measure of how similar each step is to the prior step) than faster walking (Kang and Dingwell, 2008a; England and Granata, 2007), but slower walking also increases variability (Beauchet et al., 2009). Variability may be an indicator of fall risk (Hausdorff et al., 2001; Verghese et al., 2009), but any deviation in walking speed from the preferred speed increases variability (Jordan et al., 2007). Further, variability in the elderly may be primarily due to muscle weakness rather than from slower speeds (Kang and Dingwell, 2008b). As speed decreases, the DS phase increases, both in time and as a percentage of step duration (Murray, 1967). During the DS period, both feet are in contact with the ground and can be used to alter gait and correct deviations, leading to improved control of gait. Because humans naturally modify the percentage of time they spend in the DS period of gait as they modulate their speed, this may explain the changes in stability with speed.

However, this change in DS percentage is done unconsciously. It is unknown if people can voluntarily alter their DS duration. If this is difficult and the DS period increases stability, then slower walking may be the easiest method to increase stability. This also implies that decreasing DS percentage without changing speed or increasing speed should result in similar gait changes for at least some of the gait cycle. It is well established that there are many changes to gait as speed increases, including increases in hip, knee and ankle ranges of motion, and larger ground reaction forces (GRF) (Han and Wang, 2011; Schwartz et al., 2008). However, it is unknown which changes are explicitly due to a change in DS

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percentage. Quantifying this is the first step in understanding how the DS phase and gait stability are related.

The purpose of this study, therefore, was to quantify how joint kinematics and GRF change as DS percentage changes independent of changes in walking speed. We hypothesized that increasing (or decreasing) DS percentage would have a similar effect as slower (or faster) walking. This naturally requires that subjects can modify their DS percentage without changing walking speed. If subjects cannot, this suggests that DS percentage and walking speed are intimately connected and that voluntarily changing one will automatically change the other. In contrast, if subjects can easily alter DS percentage, then speed and DS percentage can be manipulated independently to affect gait stability.

2. Methods

2.1. Participants

16 young (18–40 years), healthy adults (8 male, 8 female) participated in this study (height: 1.72 ± 0.07 m; mass: 72.8 ± 11.6 kg). All could walk continuously for 30 min without assistance or difficulty. One subject could not complete the task; his data are omitted. Each participant gave informed consent prior to testing. The study was approved by the university's Institutional Review Board.

2.2. Protocol

Subjects walked on a split-belt instrumented treadmill (Bertec, Columbis, OH) set at a constant, subject-selected speed. They were asked to walk with a normal, decreased, or increased DS percentage, both with and without feedback. Kinematic data were collected at 100 Hz using 14 cameras (Vicon, Oxford, UK) and GRF data were collected at 1000 Hz. Subjects chose a slow, comfortable pace (0.922 ± 0.110 m/s) during a preliminary trial used to establish baseline values. This speed was used for all six one-minute trials, and this cadence (100 ± 11 steps/min) was specified with audible feedback in three trials. The normal DS percentage ($31.6 \pm 3.10\%$) was used as the baseline for changing DS percentage. Subjects then walked with a normal, decreased, or increased DS fraction during six experimental trials. They practiced until they felt they were walking as requested and were comfortable with the new gait, usually from 2 to 5 min, then data was collected for 60 s. For altered DS trials, the goal was a change of 25% from the normal DS percentage. When collecting pilot data, this change was attainable and produced a noticeable change in gait. During one block of three trials, a metronome dictated the step frequency, and the DS percentage for each step was shown as a point on a plot displayed in front of the treadmill. A band indicating the desired range of DS percentage ($\pm 10\%$ of the desired value) was also shown. Subjects were asked to step in time with the metronome and keep the points within the bands by changing DS percentage. During the other block, no feedback was provided. The order of the trials within each block was randomized. The order of the feedback blocks were also randomized.

2.3. Data analysis

Kinematic data were calculated using the Plug-in Gait lower body model (Vicon, Oxford, UK) and standard processing methods. Force plate data were filtered using a zero-lag 4th-order low-pass Butterworth filter with a 20 Hz cut-off frequency. Stride events were found using the vertical GRF with a 5 N threshold. The parameters analyzed are DS, single support (SS), and stance times, step cadence, DS percentage, hip, knee, and ankle angles in the sagittal plane, swing foot height, and vertical and horizontal GRF in the sagittal plane. The SS time is the same as swing time. The gait is approximately symmetric so stride cadence is approximately half of step cadence. Step length is not explicitly examined because walking speed is held constant, so changes to step cadence are proportional to changes in step length. Two-sided t-tests were used to determine statistically significant differences. Values were statistically significant when $\alpha \leqslant 0.001$, which corresponds to $\alpha \leqslant 0.05$ after using Bonferroni correction. The denotation used for the trials will be Short, Normal, or Long, to indicate the DS percentage, FB to indicate if feedback is present, and a subscript indicating whether feedback was given in the first half of the trials ($_{FB1}$) or the second half of the trials ($_{FB2}$), e.g. ShortFB$_{FB1}$ (meaning a short DS period with feedback and feedback was given in the first block) or Long$_{FB2}$ (meaning a long DS period without feedback and feedback was given in the second block).

3. Results

3.1. Subject performance

As expected, when walking with a normal DS percentage, most subjects (14/15) maintained their normal cadence within $\pm 8\%$ between trials with and without feedback.

When shortening DS with feedback, all subjects maintained their normal cadence within $\pm 8\%$ (Table 1). When feedback was removed (Short$_{FB1}$), cadence only differed by $2\% \pm 11\%$ compared to NormalFB. In contrast, when subjects first decreased DS percentage without feedback (Short$_{FB2}$), they decreased cadence by $11\% \pm 10\%$ (from 1.64 to 1.46 Hz). All subjects decreased their DS fraction with feedback, and most (14/15) decreased it without feedback (Fig. 1, Table 1). The single trial without a decreased DS percentage was omitted in the analysis. Subjects who received feedback during block one reduced their DS percentage by approximately the same amount for both trials ($25\% \pm 10\%$ vs $25\% \pm 8\%$, $p = 0.878$). In contrast, when subjects received feedback during block two they reduced their DS percentage more during the first shortened DS trial without feedback (Short$_{FB2}$) than the second trial with feedback (ShortFB$_{FB2}$) ($32\% \pm 10\%$ vs $25\% \pm 11\%$, $p \ll 0.001$). This was primarily due to a longer SS duration for the no feedback condition. While there were statistically significant differences in the DS time, SS time, and DS percentage between ShortFB$_{FB1}$ and ShortFB$_{FB2}$ trials, the magnitude of these differences were relatively small.

When increasing DS with feedback provided first, subjects altered cadence in an attempt to increase DS percentage. For trials with feedback (LongFB$_{FB1}$), step cadence increased by $12\% \pm 14\%$ (from 1.69 to 1.90 Hz), and for the trials without feedback (Long$_{FB1}$), step cadence increased by $8.5\% \pm 19\%$ (from 1.69 to 1.84 Hz), both compared to NormalFB trials. When increasing DS with no feedback initially, step cadence did not change (Table 1). Most subjects were not able to substantially increase their DS percentage, only increasing it by $4\% \pm 14\%$ (Fig. 1, Table 1). Even with feedback, some subjects (4/15) decreased their DS percentage below normal gait. Two subjects increased their DS percentage by over 10%. Both subjects were only able to increase DS percentage while also changing cadence even with the metronome constraint. Subjects who received feedback during block one slightly, but significantly, increased their DS percentage compared to NormalFB ($6.4\% \pm 11\%$ with feedback and $4.5\% \pm 12\%$ without feedback, Fig. 1, Table 1). In contrast, subjects who received feedback during block two did not change DS percentage compared to NormalFB.

3.2. Kinematics

The hip angle from heelstrike to contralateral heelstrike was similar to normal DS conditions for all shortened DS conditions (Fig. 2). Hip flexion from contralateral heelstrike through swing

Table 1
Temporal values. All 12 conditions (3 DS percentages × 2 feedback blocks × 2 feedback orders) are given. Normal, Short, and Long indicate the DS percentage trial, ___FB indicates that feedback was present during the trial, and the subscript $\_\_\__{FB1}$ (or $\_\_\__{FB2}$) indicate that feedback was given in block one (or block two). Mean ± S.D. given.

Feedback First						
	$Normal_{FB1}$	$NormalFB_{FB1}$	$Short_{FB1}$	$ShortFB_{FB1}$	$Long_{FB1}$	$LongFB_{FB1}$
DS Time (s)	$0.189 \pm 0.023^{\dagger}$	0.185 ± 0.021	$0.140 \pm 0.026^{\ddagger}$	$0.142 \pm 0.020^{\ddagger}$	0.184 ± 0.042	$0.177 \pm 0.030^{\dagger\star}$
SS Time (s)	0.404 ± 0.025	0.407 ± 0.020	$0.459 \pm 0.051^{\ddagger}$	$0.463 \pm 0.029^{\ddagger\star}$	$0.380 \pm 0.077^{\ddagger}$	$0.357 \pm 0.046^{\ddagger\star}$
Stance Time (s)	0.782 ± 0.060	0.779 ± 0.050	$0.741 \pm 0.081^{\ddagger}$	$0.748 \pm 0.055^{\ddagger}$	$0.745 \pm 0.143^{\ddagger}$	$0.713 \pm 0.090^{\ddagger\star}$
Step Cadence (Hz)	1.696 ± 0.106	1.692 ± 0.084	1.689 ± 0.181	$1.659 \pm 0.111^{\ddagger\star}$	$1.836 \pm 0.329^{\ddagger}$	$1.900 \pm 0.229^{\ddagger\star}$
DS Percentage (%)	$0.318 \pm 0.027^{\ddagger}$	0.312 ± 0.027	$0.234 \pm 0.032^{\ddagger}$	$0.234 \pm 0.025^{\ddagger}$	$0.326 \pm 0.038^{\ddagger}$	$0.332 \pm 0.034^{\ddagger}$
Feedback Second						
	$Normal_{FB2}$	$NormalFB_{FB2}$	$Short_{FB2}$	$ShortFB_{FB2}$	$Long_{FB2}$	$LongFB_{FB2}$
DS Time (s)	$0.201 \pm 0.019^{\Delta}$	$0.200 \pm 0.019^{\Delta}$	$0.153 \pm 0.017^{\ddagger\Delta}$	$0.148 \pm 0.021^{\ddagger\star\Delta}$	$0.212 \pm 0.074^{\ddagger\Delta}$	$0.204 \pm 0.042^{\Delta}$
SS Time (s)	$0.407 \pm 0.029^{\dagger\Delta}$	$0.411 \pm 0.033^{\Delta}$	$0.543 \pm 0.080^{\ddagger\Delta}$	$0.457 \pm 0.044^{\ddagger\star\Delta}$	$0.420 \pm 0.069^{\Delta}$	$0.406 \pm 0.042^{\star\Delta}$
Stance Time (s)	$0.810 \pm 0.047^{\Delta}$	$0.809 \pm 0.049^{\Delta}$	$0.846 \pm 0.081^{\ddagger\Delta}$	$0.754 \pm 0.044^{\ddagger\star}$	$0.846 \pm 0.201^{\ddagger\Delta}$	$0.815 \pm 0.093^{\Delta}$
Step Cadence (Hz)	1.650 ± 0.094	$1.643 \pm 0.097^{\Delta}$	$1.455 \pm 0.165^{\ddagger\Delta}$	$1.660 \pm 0.109^{\bigstar}$	$1.640 \pm 0.281^{\Delta}$	$1.656 \pm 0.154^{\Delta}$
DS Percentage (%)	$0.331 \pm 0.026^{\dagger\Delta}$	$0.327 \pm 0.030^{\Delta}$	$0.223 \pm 0.033^{\ddagger\Delta}$	$0.246 \pm 0.035^{\ddagger\star\Delta}$	$0.329 \pm 0.049^{\Delta}$	0.332 ± 0.048

Stastistical significance from NormalFB $^{\dagger}p < 0.05$,$^{\ddagger}p < 0.001$. Statistical significance between Short and ShortFB or between Long and LongFB $^{\bigstar}p < 0.001$.
Statistical significance between $\_\_\__{FB1}$ and $\_\_\__{FB2}$ $^{\Delta}p < 0.001$.

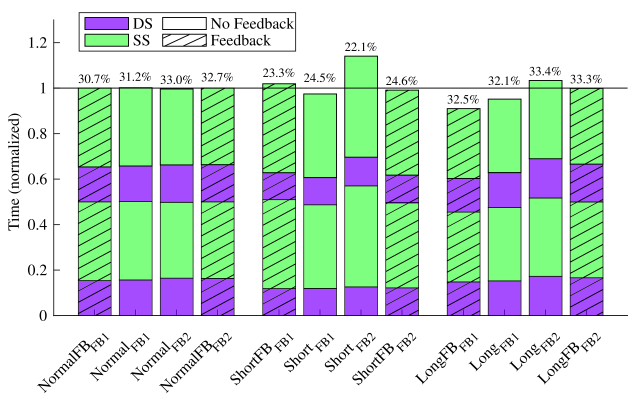

Fig. 1. Step temporal values. The purple area indicates the double support (DS) period while the green area indicates the single support (SS) period, the hatching indicates feedback was present during the trial, and the number above each column indicates the mean DS percentage for each trial type. Each column sums to the total normalized stride time, where time was normalized by the stride time of the normal DS trial with feedback. Normal, Short, and Long indicate the DS percentage trial; ___FB indicates that feedback was provided; the subscript $\_\_\__{FB1}$ (or $\_\_\__{FB2}$) indicate that feedback was given in block one (or block two). These labels will be used for all figures and tables. The feedback trials (indicated with ___FB and hatching) should sum to 1, due to the metronome dictating step frequency. All Normal trials are similar, regardless of if feedback is present or the feedback order. For all shortened DS trials, the DS period was shortened to approximately the same duration, but the increase in the SS period changed between conditions. When feedback was given in block one, the stride time remained similar even after feedback was removed (see $Short_{FB1}$). When feedback was given in block two, the stride time was reduced after feedback was added (compare $Short_{FB2}$ with $ShortFB_{FB2}$). For all long DS trials, the DS percentage did not increase much above the normal DS trials. Further, when feedback was provided first, subjects generally did not maintain the dictated step frequency, unlike when feedback was provided second.

increased for shortened DS trials compared to normal DS trials. Peak flexion significantly increased by $43\% \pm 25\%$ (from 30° to 43°) for $Short_{FB1}$ and $ShortFB_{FB1}$ (Table 2). It appeared to increase for $Short_{FB2}$ and $ShortFB_{FB2}$, but the change was not statistically significant. When increasing DS percentage from normal, hip flexion increased slightly during the first half of the stride and at the very end of the stride (Fig. 2, Table 3), but this change was not statistically significant. The knee angle from heelstrike to contralateral heelstrike was similar between conditions, although all altered DS gaits have somewhat more knee flexion on average compared to normal DS trials, but these differences were not statistically significant (Fig. 2). Knee flexion from contralateral heelstrike through swing increased for short DS trials compared to normal DS trials, with peak flexion increasing significantly by $34\% \pm 18\%$ (from 64° to 84°) for $Short_{FB1}$ and $ShortFB_{FB1}$. Knee flexion appeared to increase in the other shortened DS trials and decrease for long DS trials, but these changes were not statistically significant (Tables 2 and 3). Interestingly, the knee angle at contralateral toe-off only changed by 6–10% between trials, suggesting that toe-off is driven by trailing knee angle (Holden et al., 1997). When modifying DS percentage, changes to ankle kinematics were not consistent, especially between subjects. Further, there were no statistical significant differences in the ankle angle data between conditions and the absolute differences were relatively small.

In an attempt to explain why increasing DS percentage was difficult, changes to vertical center of mass (COM) displacement were calculated because many kinematic changes during stance were similar to reducing vertical COM displacement (Ortega and Farley, 2005; Saunders et al., 1953). However, approximately half of the subjects decreased while the others increased COM displacement from normal (Fig. 6). Additionally, there is only weak correlation between increasing DS percentage and decreasing COM displacement.

3.3. Foot height

When decreasing DS percentage from normal, swing foot height increased by $26\% \pm 24\%$ (from 273 mm to 344 mm) for $ShortFB_{FB1}$ (Fig. 3, Table 2). This increase was greatest for $Short_{FB2}$ but was statistically significant for all short DS conditions. When increasing DS percentage from normal, swing foot height decreased by $11\% \pm 14\%$ (from 273 mm to 243 mm) for $LongFB_{FB1}$ (Fig. 3, Table 3). This decrease was greatest for $Long_{FB1}$ but was statistically significant for all long DS conditions. The timing of the peak foot height relative to the total step time did not change. Because the SS time changed, the timing of the peak foot height relative to the swing phase did change.

3.4. Ground reaction forces

In all short DS trials, the initial peak vertical GRF increased significantly by 10–15% (from 1.021 bodyweights to 1.166 bodyweights) compared to normal DS trials, but the second peak did not change (Fig. 4, Table 2). The anterior-posterior GRF peaks increased in magnitude; this change was statistically significant for $Short_{FB1}$ (both peaks), $ShortFB_{FB1}$ (second peak) and $Short_{FB2}$

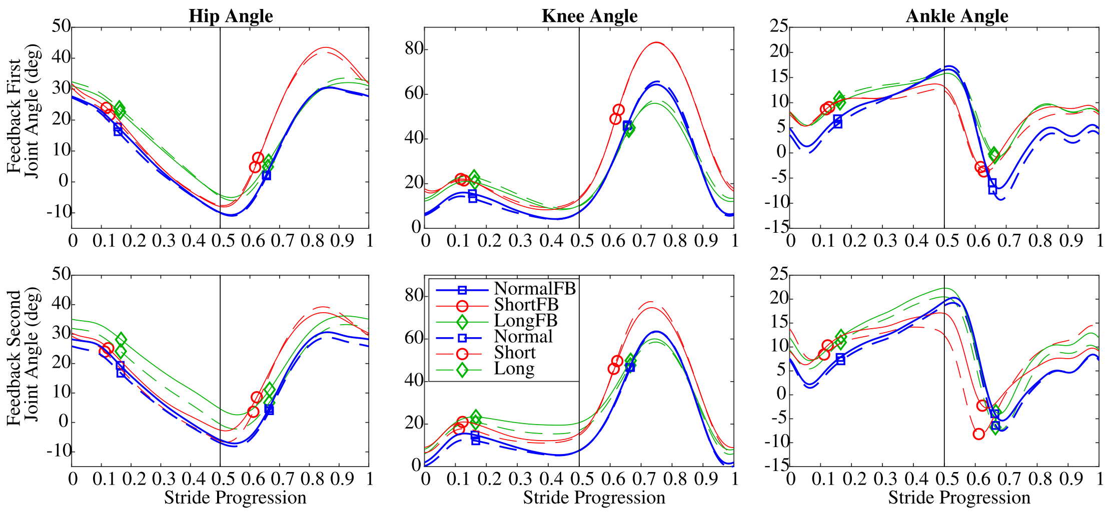

Fig. 2. Joint angles. All six trials for each feedback block are plotted together. Markers represent contralateral and ipsilateral toe off, and the vertical line represents contralateral heel strike. Normal, Short, and Long indicate the DS percentage trial and ___FB indicates that feedback was present during the trial. The data is provided in tabular form in the supplemental material. Decreasing DS percentage results in small changes during the first half of the stride and large changes during the second half of the stride. Attempting to increase DS percentage results in larger changes during the first half of the stride and small changes during the second half of the stride. When feedback was given in block one, the differences between the feedback and no feedback trials are small.

Table 2
Results for differences between normal and short DS percentage gait. Column labels are explained in Fig. 1. Mean ± S.D. given.

Feedback First				
	$Normal_{FB1}$	$NormalFB_{FB1}$	$Short_{FB1}$	$ShortFB_{FB1}$
Peak Swing Heel Height (mm)	274.1 ± 14.4	272.5 ± 18.2	$347.6 \pm 46.1^{‡}$	$343.8 \pm 53.6^{‡}$
Peak Hip Flexion (deg)	30.48 ± 4.35	30.37 ± 4.38	$41.83 \pm 8.59^{‡}$	$43.61 \pm 8.28^{‡}$
Peak Knee Flexion (deg)	65.41 ± 6.79	64.09 ± 6.47	$83.75 \pm 12.22^{‡}$	$83.94 \pm 13.75^{‡}$
Ankle ROM (deg)	27.07 ± 6.01	24.60 ± 5.65	21.86 ± 3.97	27.29 ± 8.91
Vertical GRF Peak 1 (% BW)	1.011 ± 0.021	1.004 ± 0.022	$1.176 \pm 0.112^{‡}$	$1.191 \pm 0.145^{‡}$
Vertical GRF Peak 2 (% BW)	1.030 ± 0.037	1.022 ± 0.037	0.983 ± 0.091	1.010 ± 0.042
Horizontal GRF Peak 1 (% BW)	0.134 ± 0.017	0.129 ± 0.018	$0.154 \pm 0.020^{‡}$	$0.161 \pm 0.034^{†}$
Horizontal GRF Peak 2 (% BW)	0.148 ± 0.016	0.144 ± 0.017	$0.179 \pm 0.028^{‡}$	$0.181 \pm 0.020^{‡}$
Feedback Second				
	$Normal_{FB2}$	$NormalFB_{FB2}$	$Short_{FB2}$	$ShortFB_{FB2}$
Peak Swing Heel Height (mm)	$288.1 \pm 25.3^{\Delta}$	$286.6 \pm 26.4^{\Delta}$	$365.1 \pm 87.7^{‡\Delta}$	$339.4 \pm 61.5^{‡\star}$
Peak Hip Flexion (deg)	29.35 ± 6.42	30.90 ± 7.29	$40.52 \pm 12.53^{†}$	37.45 ± 10.32
Peak Knee Flexion (deg)	63.65 ± 6.49	63.93 ± 6.73	$80.14 \pm 18.58^{†}$	$75.64 \pm 10.39^{†}$
Ankle ROM (deg)	27.40 ± 6.71	26.57 ± 7.12	$20.33 \pm 2.75^{†}$	21.05 ± 7.40
Vertical GRF Peak 1 (% BW)	1.033 ± 0.043	1.036 ± 0.048	$1.125 \pm 0.061^{‡}$	$1.172 \pm 0.064^{‡}$
Vertical GRF Peak 2 (% BW)	1.020 ± 0.038	1.009 ± 0.043	1.003 ± 0.046	0.990 ± 0.053
Horizontal GRF Peak 1 (% BW)	0.122 ± 0.029	0.136 ± 0.026	$0.171 \pm 0.031^{†}$	0.155 ± 0.032
Horizontal GRF Peak 2 (% BW)	0.147 ± 0.026	0.150 ± 0.025	$0.202 \pm 0.035^{‡}$	$0.178 \pm 0.031^{†}$

Stastistical significance from NormalFB $^{†}p < 0.05$,$^{‡}p < 0.001$. Statistical significance between Short and ShortFB.
$^{\star}p < 0.001$. Statistical significance between $\_\_\__{FB1}$ and $\_\_\__{FB2}$ $^{\Delta}p < 0.001$. % BW = bodyweight.

(second peak). For long DS trials, the magnitudes of both anterior-posterior and the second vertical GRF peaks decreased compared to normal DS trials (Fig. 4, Table 3), but these changes were not statistically significant.

3.5. Effect of feedback order

To determine what effect the feedback and feedback order had on the results, the trials are compared. When feedback was given in block one, shortened DS trials with and without feedback were very similar with no meaningful differences in any of the parameters examined, and lengthened DS trials with and without feedback had statistically significant, but not meaningful, changes in the temporal data (Fig. 1). When feedback was given second, differences between the two shortened DS trials were greater, both in magnitude and in terms of statistical significance. Specifically, subjects had longer SS periods and lower DS percentage in the no feedback trials. Additionally, step cadence was lower and peak swing foot height was higher than with feedback present. In contrast, the two long DS trials were very similar. Feedback order had a significant effect on short DS trials without feedback ($Short_{FB1}$ vs. $Short_{FB2}$) and the long DS trials with and without feedback. There were many meaningful and statistically significant differences between the two pools of subjects for these trials (Tables 1–3, Fig. 5). These differences include changes in SS, DS, and stance times, step cadence, DS percentage (Short), and swing foot height. However, there were no meaningful differences between the short DS trials with feedback.

Table 3
Results for differences between normal and long DS percentage gait. Column labels are explained in Fig. 1. Mean ± S.D. given.

Feedback First				
	$Normal_{FB1}$	$NormalFB_{FB1}$	$Long_{FB1}$	$LongFB_{FB1}$
Peak Swing Heel Height (mm)	275.9 ± 14.2	272.5 ± 18.2	$241.1 \pm 40.2^{\ddagger}$	$242.6 \pm 37.0^{\ddagger}$
Peak Hip Flexion (deg)	30.48 ± 4.35	30.37 ± 4.38	$34.62 \pm 6.68^{\dagger}$	32.94 ± 7.00
Peak Knee Flexion (deg)	65.41 ± 6.79	64.09 ± 6.47	$58.16 \pm 7.92^{\dagger}$	$56.68 \pm 6.88^{\dagger}$
Ankle ROM (deg)	27.07 ± 6.01	24.60 ± 5.65	23.81 ± 12.12	20.76 ± 7.78
Vertical GRF Peak 1 (% BW)	1.011 ± 0.021	1.004 ± 0.022	$1.056 \pm 0.068^{\dagger}$	1.027 ± 0.054
Vertical GRF Peak 2 (% BW)	1.030 ± 0.037	1.022 ± 0.037	$0.961 \pm 0.064^{\dagger}$	$0.971 \pm 0.048^{\dagger}$
Horizontal GRF Peak 1 (% BW)	0.134 ± 0.017	0.129 ± 0.018	0.134 ± 0.035	$0.109 \pm 0.017^{\dagger}$
Horizontal GRF Peak 2 (% BW)	0.148 ± 0.016	0.144 ± 0.017	0.136 ± 0.033	$0.121 \pm 0.020^{\dagger}$
Feedback Second				
	$Normal_{FB2}$	$NormalFB_{FB2}$	$Long_{FB2}$	$LongFB_{FB2}$
Peak Swing Heel Height (mm)	$288.1 \pm 25.3^{\Delta}$	$286.6 \pm 26.4^{\Delta}$	$279.0 \pm 31.8^{\ddagger\Delta}$	$270.2 \pm 33.5^{\ddagger\Delta\star}$
Peak Hip Flexion (deg)	29.35 ± 6.42	30.90 ± 7.29	35.28 ± 11.02	37.36 ± 10.58
Peak Knee Flexion (deg)	63.65 ± 6.49	63.93 ± 6.73	60.33 ± 8.55	60.23 ± 9.90
Ankle ROM (deg)	27.40 ± 6.71	26.57 ± 7.12	30.64 ± 13.92	29.40 ± 16.54
Vertical GRF Peak 1 (% BW)	1.033 ± 0.043	1.036 ± 0.048	1.010 ± 0.040	1.019 ± 0.043
Vertical GRF Peak 2 (% BW)	1.020 ± 0.038	1.009 ± 0.043	0.985 ± 0.046	0.993 ± 0.057
Horizontal GRF Peak 1 (% BW)	0.122 ± 0.029	0.136 ± 0.026	0.125 ± 0.029	0.115 ± 0.038
Horizontal GRF Peak 2 (% BW)	0.147 ± 0.026	0.150 ± 0.025	0.146 ± 0.027	0.130 ± 0.043

Stastistical significance from NormalFB $^{\dagger}p < 0.05$,$^{\ddagger}p < 0.001$. Statistical significance between Long and LongFB.$^{\star}p < 0.001$. Statistical significance between $\_\__{FB1}$ and $\_\__{FB2}$ $^{\Delta}p < 0.001$. % BW = bodyweight.

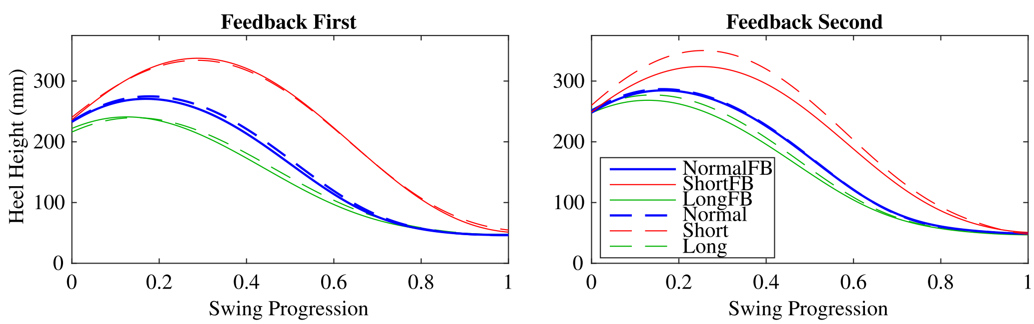

Fig. 3. Swing foot height. All six trials for each feedback group are plotted together. Normal, Short, and Long indicate the DS percentage trial and ___FB indicates that feedback was present during the trial. Decreasing DS percentage results in a higher swing foot height while attempting to increase DS percentage results in a lower swing foot height. When feedback was given in block one, the differences between the feedback and no feedback trials are small.

4. Discussion

Consciously altering DS percentage without changing speed altered gait in a manner similar to changes seen when altering walking speed, as expected. These changes were particularly obvious when decreasing DS percentage and include increased SS time, decreased DS time, increased joint range of motion, and increased GRF. Attempting to increase DS percentage changed gaits to a lesser degree, likely because subjects barely increased DS percentage.

The kinematic changes when decreasing DS percentage, while similar to changes occurring due to altering speed (Han and Wang, 2011; Winter, 1991; van Hedel et al., 2006), show distinct differences, indicating that they can be separated. Compared to increasing speed, consciously shortening DS percentage produces greater kinematic changes during the swing period and lesser changes during the stance period. This is most evident with hip and knee flexion during swing. When decreasing DS percentage while keeping walking speed constant, peak hip flexion increased 10°, but when walking faster to achieve a similar DS percentage, peak hip flexion increased only 4° (van Hedel et al., 2006). Similarly, peak knee flexion increased 18° when just decreasing DS percentage but only 5° when increasing walking speed (Fig. 2). Compared to shortening DS percentage, consciously attempting to lengthen the DS percentage produces greater changes during the stance period. This is one possible explanation of why increasing the DS percentage is so hard. Altering stance leg kinematics will also alter hip velocity, which must on average match walking speed (Martin and Schmiedeler, 2014). Thus, altering stance kinematics may make matching treadmill speed difficult. Adjusting swing leg velocity as was done when shortening the DS percentage is easier because hip velocity is unaffected (Martin et al., 2014).

It is not entirely clear why subjects altered their stance leg kinematics when attempting to lengthen the DS percentage. Because joint angle changes during stance were similar to reducing vertical COM displacement (Ortega and Farley, 2005; Saunders et al., 1953), subjects may be attempting to keep COM height constant and walk less like an inverted pendulum (Kuo, 2007). In robotics, biped gaits with long DS periods also tend to keep the COM height relatively constant (Kajita and Tani, 1991), so it reasonable that humans might attempt to do so as well. However, only about half of the subjects decreased their vertical COM displacement compared to normal (Fig. 6). Some even increased it. Of the two subjects who significantly increased their DS percentage, one decreased and the other increased their vertical COM displacement. Thus,

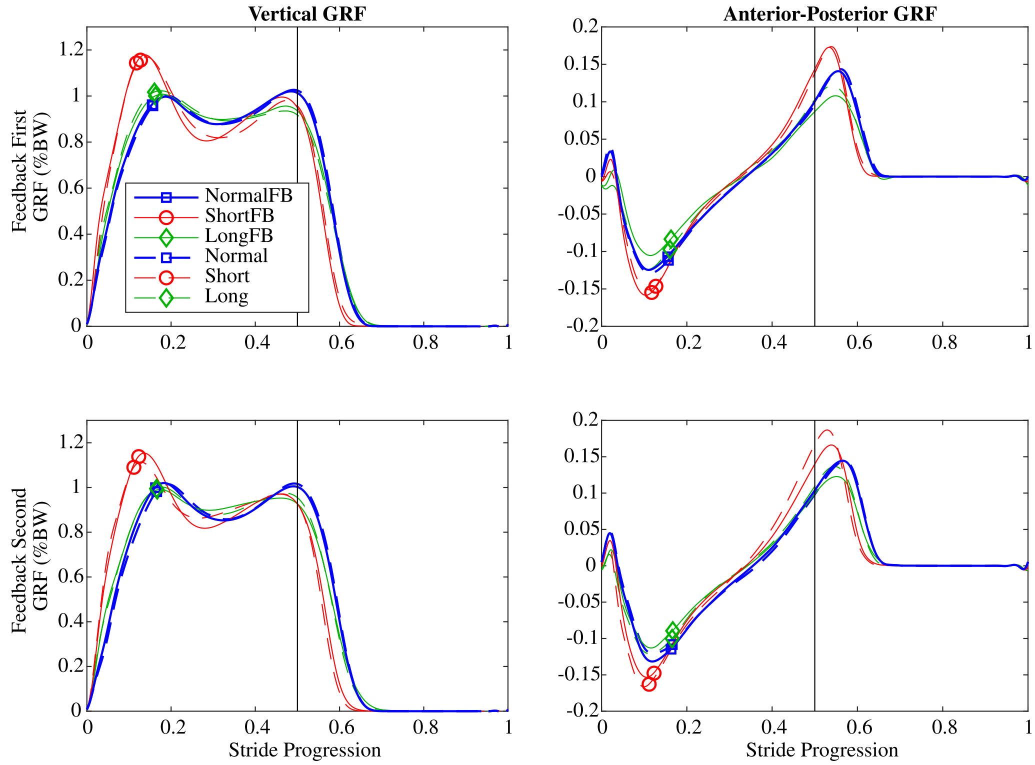

Fig. 4. Ground reaction forces. All six trials for each feedback group are plotted together. Markers represent contralateral toe off, and the vertical line represents contralateral heel strike. Normal, Short, and Long indicate the DS percentage trial and ___FB indicates that feedback was present during the trial. BW = bodyweight. Decreasing DS percentage results in larger GRF magnitudes during all peaks except the second vertical GRF peak. The changes when attempting to increase DS percentage are smaller than when decreasing DS percentage.

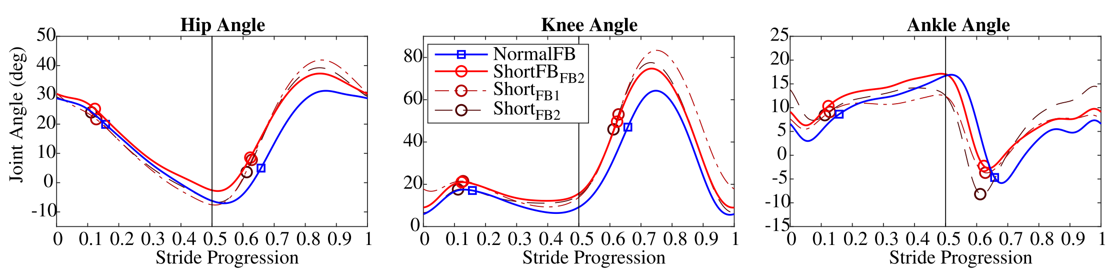

Fig. 5. Joint angles. Markers represent contralateral and ipsilateral toe off, and the vertical line represents contralateral heel strike. Legend labels are explained in Fig. 1. These three shortened DS trials were the most different from the NormalFB trials and from each other and are shown here to make their comparisons easier. The Short$_{FB1}$ trial had the largest difference from normal at the hip and knee. The change mostly occurred during the second half of the stride.

decreased COM displacement is neither necessary nor sufficient to increase DS percentage. Given the available data, it is unclear why some subjects were able to increase their DS percentage. Due to the few number of subjects who successfully increased their DS percentage, there are no apparent differences in the gaits of the subjects who were able to do this and the subjects who could not.

Similar to joint kinematics, GRF changes when shortening DS percentage are similar to those seen with faster walking, with most peaks increasing. The increased peaks in anterior-posterior GRF are similar to faster anterior-posterior swaying (Lorenzo and Vanrenterghem, 2015), which is expected because the COM must move faster during a shorter DS period. The larger first vertical GRF peak may be a result of faster COM velocity during the DS period, as the velocity needs to be redirected from downward to upward during a shorter time (Kuo, 2007). When the DS period is shortened, the available time for redirection is reduced. However, the required velocity change remains constant. Thus, the acceleration must increase, which requires larger forces. This explains the larger magnitude in the first vertical GRF peak, but not why the second peak remains constant. There may be conflicting task goals of propelling the COM faster and lifting the rear foot off the ground more quickly. Propelling the COM faster would increase vertical GRF while lifting the rear foot off the ground more quickly would decrease vertical GRF.

The consistent second vertical GRF peak may also be due to the influence of the push-off force on speed. In very simple physics-based models of gait, speed is typically highly dependent on push-off force (Kuo, 2002). Further, changing the push-off impulse for a given speed alters step period and leg angle (McGeer, 1991). Because walking speed was kept constant here, keeping a constant vertical push-off force may aid in achieving the correct speed.

To decrease DS percentage without changing walking speed, the time spent in SS needs to be increased. This can be accomplished by either slowing foot velocity and maintaining the same trajectory or moving the foot through a longer path by lifting it higher.

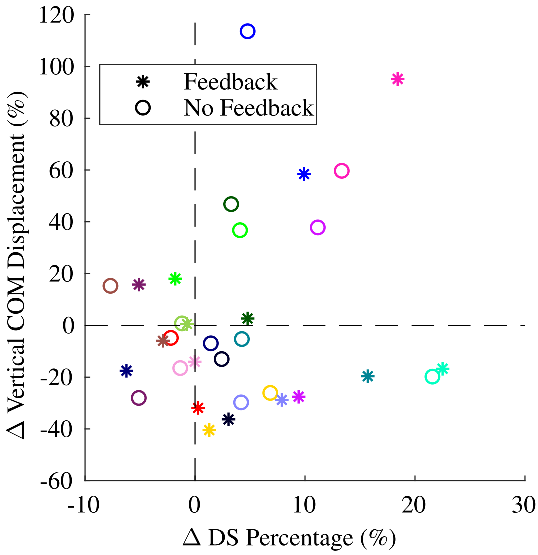

Fig. 6. Change in vertical COM displacement compared to the change in DS percentage during long (Long and LongFB) DS trials. Markers indicate the average for one subject during one trial, the marker shape indicates whether feedback was present during the trial, and the colors indicate individual subjects. The axes indicate the percent change from the NormalFB trial and the dashed lines indicate zero mean change. Although most subjects at least slightly decreased vertical COM displacement, this decrease was not sufficient to increase DS percentage. Some subjects were able to increase DS percentage while also increasing vertical COM displacement, indicating that decreasing vertical COM displacement is not necessary to increase DS percentage.

Subjects chose the latter. The opposite occurs for an increased DS percentage. Because initial foot velocity is largely dictated by the speed at which the foot lifts off the ground, work is required to change foot speed. This would likely increase metabolic cost, which is usually undesirable (Kuo, 2007). On the other hand, changing the foot trajectory does not require as much work. Thus, the change in swing foot trajectory may reduce energy expenditure.

Finally, feedback order altered subjects' shortened DS gaits. When subjects received no feedback during block one, they decreased cadence. They then changed their gait to accommodate the cadence constraint imposed during block two. When subjects received feedback during block one, they first found a gait without changing cadence. Based on the negligible differences when feedback was removed during block two, it appears subjects simply reused their learned gait. Because humans are biased toward repeated motions (Verstynen and Sabes, 2011), this is expected.

A limitation of this study is the relatively short training period. This may be a reason most subjects were unable to increase DS percentage. However, about half of the subjects did increase DS percentage over the duration of the trial. Given that they increased DS percentage by 2–5% over 100 steps, they may have performed better with several additional minutes of practice. Removing the step cadence constraint and some coaching may have helped as well. Regardless, increasing DS percentage is difficult.

Unfortunately, we are unable to directly analyze stability in this study. Joint variability may indicate increased fall risk, however variability increased with both a decrease and an attempted increase in DS percentage making it difficult to tell if stability is altered. The difficulty of increasing DS percentage suggests that people may naturally walk with the largest DS percentage easily achieved and must slow down to increase DS percentage. Because an increased DS percentage may increase disturbance rejection capabilities, this may explain why people slow down when they feel unstable. It may also explain why elderly adults walk faster after balance intervention programs such as tai chi (Li et al., 2005).

5. Conclusions

For a constant walking speed, decreasing DS percentage is relatively easy while increasing DS percentage is hard. To accommodate a modified DS fraction without changing speed, subjects changed their gait. When decreasing DS percentage, most kinematic changes occurred during swing. Peak hip and knee flexion increased, as did swing foot height. In general, attempting to increase DS percentage resulted in changes in the opposite direction. However, subjects also altered their stance leg kinematics. The changes are similar to, but distinct from, those made when altering speed.

Declaration of Competing Interest

The authors declare that there is no conflict of interest associated with this work.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2019.05.028.

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