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A new approach to detecting asymmetries in gait

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Abstract

Background. Traditional parameters used to assess gait asymmetries, e.g., joint range of motion or symmetry indices, fail to provide insight regarding timing and magnitude of movement deviations among lower limb joints during the gait cycle. This study evaluated the efficacy of a new approach for quantifying aspects of gait asymmetry.

Methods. Asymmetric gait was simulated by joint bracing. The dominant leg knee or ankle was constrained in ten healthy young adult males. Kinematic data were collected during three-minute trials for treadmill-walking conditions: unbraced, knee-braced, and ankle-braced. We created a *regions of deviation* analysis, which compared asymmetric walking (flexion/extension behavior) relative to normative (group-averaged unbraced) data. Symmetry/asymmetry between bilateral joint pairs was quantified and the behavior of specific joints relative to normative data was assessed using this analysis.

Findings. While traditional measures (e.g., maximum range of motion) grossly detected asymmetries due to bracing, these new analyses identified significant regions of asymmetry. Knee-bracing affected the knee during mid-swing, but also increased ankle asymmetry during both terminal stance and mid-swing and hip asymmetry during mid-stance and mid-swing. Ankle-bracing created asymmetries at the ankle (terminal stance and initial swing) and hip (terminal stance), but none at the knee.

Interpretation. Region of deviation analysis effectively identified the timing and magnitude of deviations *throughout* the gait cycle, and provided information about the impact of a joint-mobility perturbation on neighboring joints. This new methodology will be useful in clinical settings to identify, characterize, and monitor recovery from asymmetric behaviors associated with injuries or pathologies.

Keywords: Gait; Bracing; Treadmill-walking

1. Introduction

Limb motion during steady-state constant speed locomotion involves complicated inter-segmental and inter-limb interactions during both normal and abnormal walking (Sadeghi, 2003). Each limb segment and joint undergoes a cyclic pattern of flexion and extension and to a lesser extent rotation, abduction and adduction during each stride. An acute injury to a lower limb can create pain and discomfort that disrupts the cyclic gait pattern, and can result in asymmetric or limping gait as an injured individual attempts to maintain the ability to walk (Perry, 1992). Understanding how restrictions to joint range of motion influence movement at other joints is important when assessing acute lower limb injury and recovery. Gait pathologies that limit function are often assessed and treated using knowledge of the patient's health history, physical examination, and gait analysis (Winter, 1990). In a clinical setting, gait analysis can consist of qualitative observation (i.e., visual inspection), quantitative laboratory measurements (e.g., step length, single support time, etc.), or a combination of the two.

During a qualitative assessment, visual inspection is used to identify subtle and obvious aspects of a patient's

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gait abnormality (Perry, 1992;Whittle, 1996). Asymmetries are often symptomatic of pathological gait and can be used to identify and track problems (Griffin et al., 1995). The basis of this type of observational gait analysis is the assumption that the coordinated movement of the lower limbs has a high degree of symmetry, and understanding asymmetries provides insight into the efficacy of treatment during rehabilitation after injury.

Because visual inspection of gait is qualitative in nature, it is often supplemented with quantitative laboratory measurements that allow for greater precision and the assessment of more complex situations (Perry, 1992). Univariate parameters such as walking speed, step length, foot rotation angle, maximum joint range of motion, and durations of stance and swing phases of gait are frequently used to assess, monitor and treat gait deficiencies (Becker et al., 1995; Bruyn et al., 2003; Chodera, 1974; Craik and Oatis, 1995; Crowe and Samson, 1997; DeVita et al., 1997; Diop et al., 2004; Draper, 2000; Grieve, 1968; Griffin et al., 1995; Hausdorff, 2004; Karamandis et al., 2003; Knoll et al., 2004; Salamon et al., 2002;Skinner and Effeney, 1985). The assumption of symmetry in univariate measures has been used to identify pathology and track recovery by characterizing asymmetries with symmetry indices and ratios (Sadeghi et al., 2000). Symmetry indices evaluate the degree of symmetric behavior by calculating the difference between left and right sides for a given parameter and dividing the result by the bilateral average. Index values close to zero indicate symmetric behavior. Symmetry indices have previously been used in several studies to determine if asymmetries exist in parameters that describe the behavior of the lower limbs. The parameters used in the indices have included vertical ground reaction forces, plantar pressure distribution, speed and stride frequencies (Sadeghi, 2003).

Unfortunately, current univariate measurements lack the ability to capture the spatio-temporal complexity of the gait cycle, and provide little information on the behavior of other joints. To effectively assess injury and monitor recovery, the effect on ipsilateral and contralateral limb joints due to restriction in range of motion to one joint needs to be understood. For example, quantitative assessments of joint ranges of motion are typically conducted at discrete and easily defined points in time (e.g., heel strike, toe-off). Such measures fail to capture the motion that occurs between these discreet events, and fail to assess how problems at one joint affect other joints.

More recently, Manal and Stanhope (2004) and Crenshaw and Richards (2006) have proposed additional methods and parameters to examine asymmetric behavior. Manal and Stanhope qualitatively compared spatio-temporal data by displaying subject-specific movement pattern deviations relative to normative data by color coding magnitude and direction of the deviations. However, this technique does not provide quantitative information for the comparison and analysis of complex movement patterns, and does not examine changes in symmetry of bilateral parameters. Crenshaw and Richards quantitatively examined joint angle symmetry and normalcy using eigenvectors to compare waveforms of joint angle data. The measures of symmetry developed in this work effectively identify joint angle behavior that is no longer symmetric and has deviated from normative measurements; however, this method does not identify the timing in the gait cycle were these deviations are occurring.

Our study introduces two new quantitative analysis methods to address limitations present in current gait assessment techniques. Both methods examine joint angular displacements and identify regions of the gait cycle that deviate from normative data. The first examines bilateral symmetry/asymmetry between joint pairs at the ankle, knee, and hip. The second identifies deviations in individual joint motion. By examining these "regions of deviation" and more specifically the timing and magnitude of peak deviations during the stance and swing phases of the gait cycle, these analyses provide quantitative metrics that can be used to describe and compare motions. To test the new methods, a data set with known asymmetries was created by restricting joint range of motion using a brace at the ankle or knee. Bracing simulates gait perturbations that result from restricted joint movement caused by injury or disability. By creating a known and repeatable gait asymmetry, we can better assess how different approaches detect, track, and quantify asymmetry. These simulated data are particularly advantageous because an individual's normal gait can be compared directly to his perturbed gait. The primary focus of this study was to evaluate the efficacy of a new approach (regions of deviation analysis) for quantifying the spatio-temporal complexity of the asymmetric gait cycle. A secondary aim was to provide insight into joint motions due to bracing of a single joint, and how this restriction affects ipsilateral and contralateral joints.

2. Methods

2.1. Participants

Ten healthy males, mean (standard deviation) age 21 (2) yrs, height 1.79 (0.09) m, and mass 81 (9) kg participated in this study. Subjects had no gait impairments, no history of significant trauma to the lower extremities or joints, and were experienced treadmill walkers. All subjects indicated right leg dominance. All procedures were approved by the University Institutional Review Board, and all participants gave informed consent.

2.2. Experimental procedure

Before data collection began, subjects changed into a sleeveless top, snug-fitting shorts, and running or walking shoes. Thirty-four reflective markers were attached to the head, torso, arms, and legs. Gait parameters were derived from markers at the bilateral anterior superior iliac spine, mid-thigh, femoral lateral epicondyle, tibial tuberosity, lateral malleolus, 1st and 5th metatarsal heads, and heel. Kinematic data were collected using a six camera infrared motion analysis system at 120 Hz (Vicon, Oxford, UK; Model 460), and were low-pass filtered at 8 Hz using a fourth-order, zero-lag, Butterworth filter.

Data were collected continuously during three-minute trials while the subject walked on a treadmill (Proform, Logan, UT, USA; Model PFTL05052) for each testing condition. Three-minute trials were selected to allow for the collection of at least 100 gait cycles per side. Gait asymmetries were created using an ankle or a knee brace (DonJoy, Vista, CA, USA; models 82,399 and 81,099, respectively) to restrict movement of the dominant leg, Fig. 1. The brace constrained joint motion by locking the knee in full extension or ankle in neutral orientation. The mass of the knee brace was 0.8 kg and the ankle brace was 1.25 kg. During braced trials, reflective markers were placed directly on the brace. Offset measurements from the markers on the brace to the underlying skin surface were recorded. These offsets were then used to adjust the data accordingly. Because the knee brace imposed the greatest walking difficulty, this constraint was used to define walking speed. The average of three self-selected comfortable speeds, chosen while wearing the knee brace, was used for all subsequent test conditions (3.2 (0.4) km/h). Otherwise participants were not provided with practice walking with the braces.

2.3. Data analysis

Kinematic data were divided into individual gait cycles for each side of the body. A gait cycle was defined from heel strike to subsequent heel strike. Data for each cycle was reduced to 100 points representing equal intervals from 0% to 100%. For analysis purposes, the functional phases of gait were described by first dividing the cycle into the stance (60%) and the swing (40%) phases of gait and then further dividing those phases into eight smaller regions: initial (0–2%) contact, loading response (2–10%), mid-stance (10–30%), terminal stance (30–50%), pre-swing (50–60%), initial swing (60–73%), mid-swing (73–87%), and terminal swing (87–100%); specific percentage for the events are defined in Perry (1992).

Fig. 1. Knee and ankle braces used to restrict joint range of motion.

2.3.1. Traditional parameters

Kinematic data were used to calculate the following univariate parameters for the right and left sides: ankle, knee, and hip maximum joint angle range of motion (RoM), step length (SL), step width (SW), foot rotation angle (FR), and single-leg support time (SLST). Flexion–extension joint angles were computed using the procedure proposed by Vaughan et al. (1999). Maximum range of motion was defined as the absolute value of the difference between the largest and smallest angles for a given cycle. Step lengths for each side were defined as the anterior–posterior (AP) distance between consecutive heel strikes of the braced (affected) or unbraced (unaffected) leg. Single-leg support time was defined as the time spent between toe-off and heel strike of the contralateral foot. Foot rotation angle was defined as the angle between the long axis of the foot and the plane defined by the x and z components of the lab coordinate system (the long axis of the treadmill belt was aligned parallel to the x axis of the lab coordinate system). Step width was defined as the medial–lateral distance between subsequent heel strikes of contralateral feet and does not have bilateral components (Vaughan et al., 1999).

For each subject, asymmetries in these univariate gait parameters were assessed using a symmetry index (Becker et al., 1995) defined as:

$$\mathrm{SI} = \frac{P_A - P_U}{0.5(P_A + P_U)} 100\% \tag{1.1}$$

where P_A is the value of an univariate parameter on the braced (right) side of the body, P_U is the value of the parameter on the unbraced (left) side. Zero values indicate no difference between sides while negative values indicate smaller values for the braced side.

2.3.2. Regions of deviation analysis

Two new techniques were developed to capture the timing and magnitude of asymmetric behavior during the gait cycle by detecting regions of deviation (ROD) from normative joint motion. Flexion–extension joint angle data were examined. Normative behavior was based on unbraced walking data averaged over all ten test subjects. The first method identified regions of deviation in bilateral joint angle symmetry, and is referred to as symmetry regions of deviation (SROD) analysis. The second identified region of deviation is an individual joint angle for a given limb, and is referred to as the individual regions of deviation (IROD) analysis. SROD analysis can detect significant joint angle asymmetry, but it cannot conclusively indicate which joint is most affected. IROD analysis is used to provide information about the behavior of the individual joints. Therefore, using these analyses together, it is possible to identify (i) which joints are affected during perturbed gait, (ii) timing and magnitude during the gait cycle when these effects are most prominent, and (iii) how a perturbation at one joint affects ipsilateral and contralateral joints.

SROD analysis determines when bilateral joint angle pairs demonstrate asymmetric behavior. To perform this procedure for a given test condition (i), first the angular difference between the braced/affected (right) and unbraced/unaffected (left) sides of a given joint (j) was computed over one gait cycle, $\Delta\theta_j^i = \theta_{j,\mathrm{Affected}}^i - \theta_{j,\mathrm{Unaffected}}^i$. A negative value indicates a smaller value for the braced side. This calculation was repeated over the three-minutes of test data (i.e., 100+ gait cycles). These bilateral joint angle differences were then averaged over the total number of cycles ($\langle\Delta\theta_j^i\rangle$, where $\langle\bullet\rangle$ indicates ensemble average over a number of samples). For a given subject, this averaged difference was then compared to normative joint motion, i.e., average ($\langle\Delta\theta_j^{\mathrm{UB,Norm}}\rangle$) and standard deviation ($\mathrm{SD}_j^{\mathrm{UB,Norm}}$) for the unbraced data of all test subjects (Eq. 1.2). Fig. 2 (top panel) illustrates graphically the technique for determining hip SROD values for a subject during the knee-braced condition.

$$\mathrm{SROD} = \begin{cases} \langle\Delta\theta_j^i\rangle - (\langle\Delta\theta_j^{\mathrm{UB,Norm}}\rangle + \mathrm{SD}_j^{\mathrm{UB,Norm}}), & \langle\Delta\theta_j^i\rangle > \mathrm{SNorm}^+ \\ \langle\Delta\theta_j^i\rangle - (\langle\Delta\theta_j^{\mathrm{UB,Norm}}\rangle - \mathrm{SD}_j^{\mathrm{UB,Norm}}), & \langle\Delta\theta_j^i\rangle < \mathrm{SNorm}^- \\ 0, & \mathrm{SNorm}^- \leqslant \langle\Delta\theta_j^i\rangle \leqslant \mathrm{SNorm}^+ \end{cases} \tag{1.2}$$

where $\mathrm{SNorm}^+ = \langle\Delta\theta_j^{\mathrm{UB,Norm}}\rangle + \mathrm{SD}_j^{\mathrm{UB,Norm}}, \mathrm{SNorm}^- = \langle\Delta\theta_j^{\mathrm{UB,Norm}}\rangle - \mathrm{SD}_j^{\mathrm{UB,Norm}}$, $i \in [\text{Unbraced (UB)}, \text{Ankle Braced (AB)}, \text{Knee Braced (KB)}]$, $j \in [\text{Ankle, Knee, Hip}]$.

Individual ROD (IROD) analysis is performed to determine the magnitude and timing of asymmetric behavior of individual joints during specific phases of the gait cycle. To perform this procedure, first each individual joint angle for each side during each 100+ gait cycles was identified and averaged $\langle\theta_j^i\rangle$. We then compared this subject-specific averaged joint angle and to normative joint motion, i.e., average ($\langle\theta_j^{\mathrm{UB,Norm}}\rangle$) and standard deviation ($\mathrm{SD}_j^{\mathrm{UB,Norm}}$) for the unbraced data of all test subjects (Eq. 1.3). Fig. 2 (bottom panel) illustrates graphically how IROD values were determined for the affected hip of one subject during the knee-braced condition.

$$\mathrm{IROD} = \begin{cases} \langle\theta_j^i\rangle - (\langle\theta_j^{\mathrm{UB,Norm}}\rangle + \mathrm{SD}_j^{\mathrm{UB,Norm}}), & \langle\theta_j^i\rangle > \mathrm{INorm}^+ \\ \langle\theta_j^i\rangle - (\langle\theta_j^{\mathrm{UB,Norm}}\rangle - \mathrm{SD}_j^{\mathrm{UB,Norm}}), & \langle\theta_j^i\rangle < \mathrm{INorm}^- \\ 0, & \mathrm{INorm}^- \leqslant \langle\theta_j^i\rangle \leqslant \mathrm{INorm}^+ \end{cases} \tag{1.3}$$

where $\mathrm{INorm}^+ = \langle\theta_j^{\mathrm{UB,Norm}}\rangle + \mathrm{SD}_j^{\mathrm{UB,Norm}}$,
$\mathrm{INorm}^- = \langle\theta_j^{\mathrm{UB,Norm}}\rangle - \mathrm{SD}_j^{\mathrm{UB,Norm}}$
$i \in [\text{Unbraced (UB)}, \text{Knee Braced (KB)}, \text{Ankle Braced (AB)}]$
$j \in [\text{RAnkle, RKnee, RHip, LAnkle, LKnee, LHip}]$.

2.4. Statistical analysis

Two-way repeated-measures ANOVA tests were used to examine how the bracing conditions and limb side affected univariate gait parameters (ankle, knee, and hip range of motion, single-leg support time, step length, and foot rotation). Repeated-measures ANOVA tests were conducted to examine how the bracing conditions affected the symmetry indices and step width. Significant main effects were further examined by LSD post-hoc comparisons. To determine how each bracing condition affected joint motion, peak SROD and IROD values (magnitude and timing) during the stance and/or swing phases were identified for each subject. Peak magnitude values were compared, via paired t-tests, to the corresponding normative unbraced value at that percentage in the gait cycle. The significance level was set at 0.05. Statistical analyses were run in SPSS (SPSS Inc., Chicago, IL; v13).

3. Results

3.1. Regions of deviation

Symmetry regions of deviation analysis identified bilateral asymmetries at each joint that were created by bracing. By plotting SROD value as a function of percent gait cycle (%GC), the magnitude and timing of peak differences in joint angles between limbs became apparent (Fig. 3).

For the knee-braced condition, SROD analysis identified that the largest asymmetries in joint movements occurred during the swing phase for all three joints. For example, peak asymmetry between knee movements occurred at mid-swing (i.e., the mean (and standard deviation) of the peak difference between the affected and

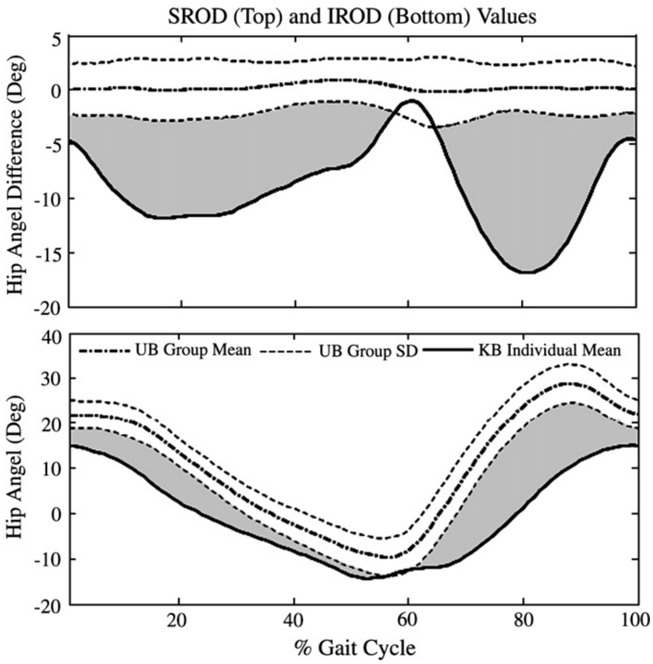

Fig. 2. Illustrative examples demonstrating techniques for determining SROD (top) and IROD (bottom) values of the hip joint for one individual during the knee-braced (KB) condition. An individual subject's mean value, over the three-minute trial, is compared to ensemble-averaged group mean and standard deviation (SD) values during the unbraced (UB) condition. Shaded areas indicate when the individual's results were beyond one SD from the UB group mean. The magnitude and timing of these shaded areas produce the SROD and IROD parameter values.

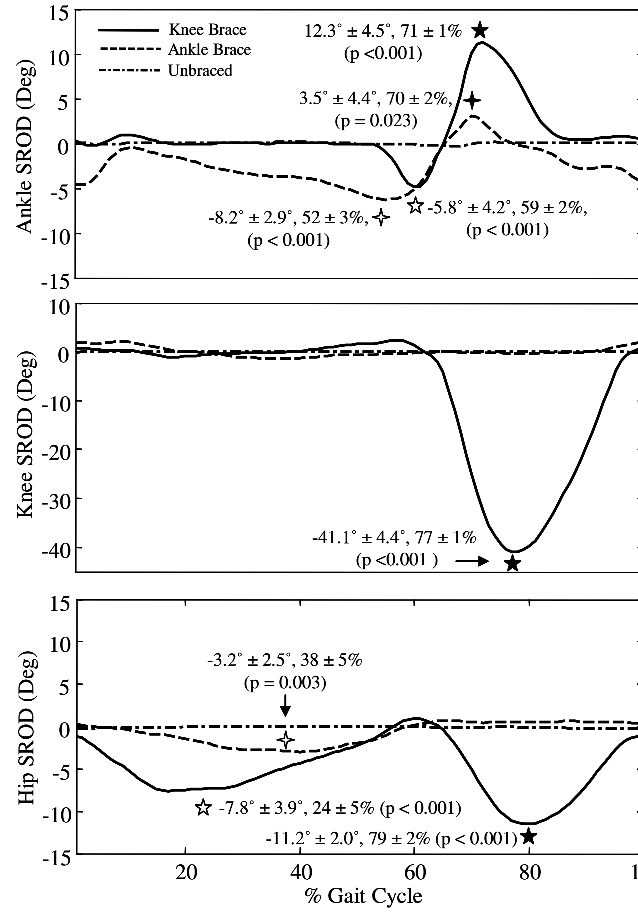

Fig. 3. SROD values, which are calculated from bilateral joint angle differences, provide spatiotemporal insight into asymmetric gait behavior. Peak values – magnitude and gait cycle timing (average ± SD) – that were significantly different from the unbraced condition are identified by five-point stars for knee-bracing and four-point stars for ankle-bracing. Open and solid stars identify peaks during stance and swing, respectively. A negative value indicates smaller angle for the braced side.

unaffected sides was $-41.1°$ (4.4°) at 77% (1%) GC). Further, this peak value was significantly different from the unbraced value, $P < 0.001$, Fig. 3 (middle panel). Knee-bracing also resulted in significant asymmetric differences at the ankles and hips during both stance and swing ($P < 0.001$). Peak differences at the ankles occurred during terminal stance and during mid-swing. Significant peak differences were also detected at the hip during mid-stance and during mid-swing.

For ankle-bracing, the largest asymmetries occurred during the stance phase. These asymmetries were smaller than for knee-bracing and significant peak differences were found only in the ankle and hip. The ankle was affected during pre-swing and during initial swing. The hip was only affected in terminal stance.

Individual regions of deviation analysis indicated that, relative to normative unbraced walking, bracing generally created large, significant asymmetries on the affected side for all joints, especially during the knee-braced condition (Fig. 4). IROD analysis also identified significant changes due to bracing in joint movements for the unbraced side. For example, compared to the unbraced condition, flexion of the hip joint on the unaffected side increased to compensate for knee-bracing during stance (4.5° at 33%GC, $P = 0.003$). Additionally, ankle-bracing created increased extension in both knees during swing. Because the change was created in the same direction at both joints, significant SROD values were not seen in the data.

3.2. Traditional parameters and symmetry indices

Traditional plots of flexion/extension angles between affected and unaffected sides suggest noticeable asymmetries in joint motion due to bracing (Fig. 5). Knee-bracing appears to have a noticeable effect on the behavior of the ankle, knee, and hip joints, while large differences in motion appear only at the ankle during ankle-bracing. Analyses of univariate measures, however, found that the maximum rang of motion values were significantly different for all joints for both conditions. Specifically, repeated-measures ANOVAs found significant interaction effects for bracing condition × limb side for all joint range of motion values, as well as single-leg support time (Table 1). Post-hoc tests revealed that the affected and unaffected sides significantly differed for the knee- and ankle-braced conditions. Additionally, affected side joint range of motion and single-leg support time values were significantly different between the three bracing conditions. Step width increased significantly for the ankle-braced

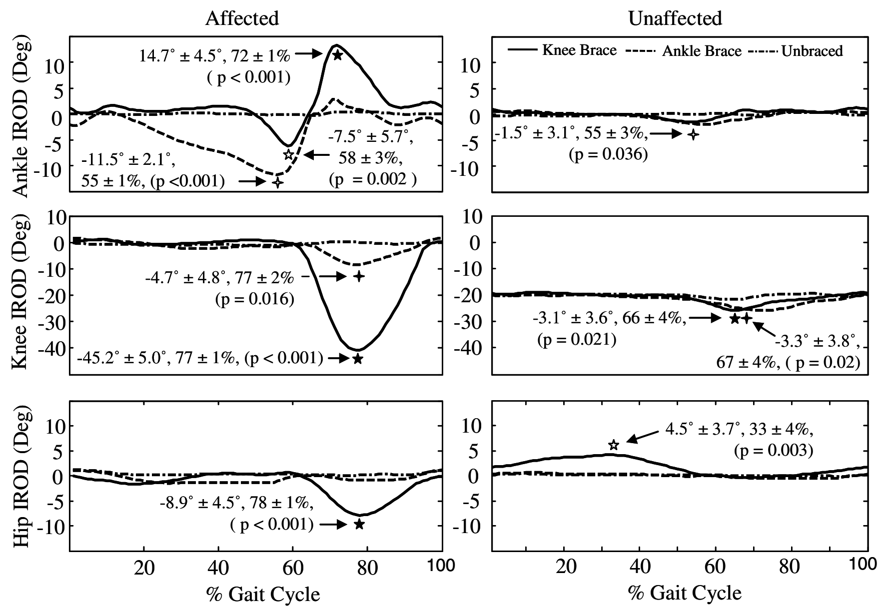

Fig. 4. Plots of average IROD values for the braced (right) and unaffected (left) ankle, knee and hip joints. See caption for Fig. 3 for explanation of symbols and numerical values.

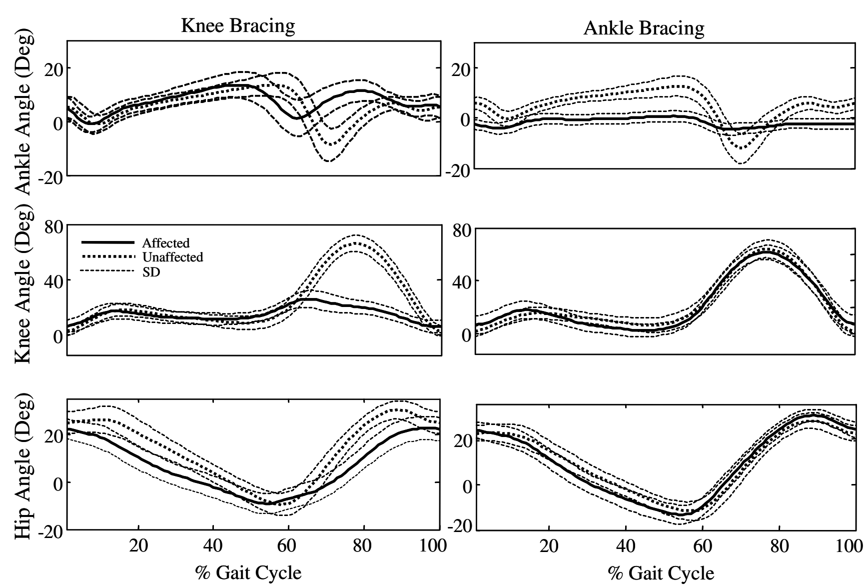

Fig. 5. Group mean joint angles for the braced (right) and unaffected (left) limbs during knee- and ankle-braced walking. Positive values indicate flexion.

condition, and was even larger for the knee-braced condition. No differences between the limbs or bracing conditions were found for step length or foot rotation angle (Table 1). Step width was normalized by the subject's inter-ASIS width and had a mean unbraced value of 0.35 (0.10). Step width increased significantly for the ankle-braced condition (0.46 (0.10), $P < 0.001$), and was even larger for the knee-braced condition (0.55 (0.16), $P < 0.001$).

Differences between affected and unaffected limb parameters were similarly observed in the symmetry indices for joint range of motion and single-leg support time, while no differences were noted for step length or foot rotation (Table 2). As expected, symmetry indices for the ankle joint range of motion were largest during the ankle-braced condition and largest for the knee joint range of motion during knee-bracing. Interestingly, knee-bracing resulted in decreased hip range of motion for the affected side (hip SI: −20.2% (7.9%)), whereas ankle-bracing resulted in increased hip range of motion (9.2% (8.3%)).

4. Discussion

Gait function depends on both coordinated motion of the body and the timing of that motion. Traditional

Table 1
Mean (and standard deviation) of the ankle, knee, and hip joint RoM, single-leg support time (SLST), step length (SL), and foot rotation angle (FR) for the three test conditions

Parameter	Unbraced		Knee brace		Ankle brace		
	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected	P[b]
Ankle RoM (Deg)	26.9 (3.8)	27.5 (4.0)	19.4 (5.0)[c,d]	25.5 (5.3)	6.6 (0.8)[c,d,e]	26.4 (4.1)	<0.001
Knee RoM (Deg)	67.3 (1)	67.6 (0.8)	22.0 (2.0)[c,d]	64.9 (1)	59.9 (1.5)[d,e]	63.2 (1.4)	<0.001
Hip RoM (Deg)	38.8 (1.0)	39.2 (0.8)	32.9 (0.9)[c,d]	40.5 (1.5)	43.7 (1.4)[c,d,e]	39.9 (1.3)	<0.001
SLST (s)	0.46 (0.02)	0.46 (0.02)	0.47 (0.03)[c]	0.5 (0.03)[d]	0.47 (0.02)z	0.48 (0.02)[c,f]	<0.001
Step length[a]	0.34 (0.02)	0.34 (0.02)	0.34 (0.01)	0.36 (0.01)	0.34 (0.008)	0.34 (0.01)	0.86
FR angle (Deg)	4.6 (4.3)	5.5 (3.9)	3.9 (2.8)	4.7 (2)	4.2 (2.4)	4.4 (2.7)	0.74

[a] Normalized by subject height.
[b] P-value for interaction effect (bracing × side) in RM ANOVA.
[c] Significantly different from unaffected side within bracing condition ($P < 0.05$).
[d] Significantly different from unbraced condition ($P < 0.05$).
[e] Significantly different from knee-braced condition on affected side ($P < 0.05$).
[f] Significantly different from knee-braced condition on unaffected side ($P < 0.05$).

Table 2
Mean (and standard deviation) for symmetry indices (%) for the ankle, knee, and hip joint RoM, single-leg support time (SLST), step length (SL), and foot rotation angle (FR). Negative value indicates smaller value for the braced side

Parameter	Unbraced	Knee-braced	Ankle-braced	P[a]
Ankle RoM	−2.1 (13.7)	−27.7 (21.2)[b]	−119 (9)[b,c]	<0.001
Knee RoM	−0.2 (3.7)	−100.3 (20.9)[b]	−4.9 (4)[b,c]	<0.001
Hip RoM	−1.1 (6.7)	−20.2 (7.9)[b]	9.2 (8.3)[b,c]	<0.001
SLST	−0.4 (2)	−5.9 (4.8)[b]	−2.1 (2.9)[c]	0.002
Step length	0.3 (4)	−4.4 (9.6)	−0.06 (6.4)	0.07
FR angle	−18.9 (71.5)	−29.4 (44.4)	1 (53.3)	0.5

[a] P-value for RM ANOVA.
[b] Significantly different from the unbraced condition ($P < 0.05$).
[c] Significantly different from the knee-braced condition ($P < 0.05$).

parameters have a limited ability to describe the impact of asymmetries in gait function because they do not provide temporal information. Regions of deviation analyses provide *quantitative* information on the timing and magnitude of deviations during the gait cycle and how a perturbation at one joint influences contralateral and ipsalateral joints. This is important because functional analyses of gait perturbations require assessment and characterization of the patterns of interactions between individual joints. (Perry, 1992).

4.1. Region of deviation analysis

ROD analysis was used to describe these affects. ROD analyses indicated that knee-bracing had a greater impact than ankle-bracing on overall joint symmetry. For knee-bracing, SROD analysis highlighted that the greatest effect on joint symmetry occurred between the knees, with the peak difference during mid-swing (peak difference between sides was −41° at 77%GC). The negative SROD value indicated that joint range of motion on the braced side of the body was reduced. Furthermore, SROD analysis showed that knee-bracing affected the ankle and hip joints during both stance and swing; however, the greatest asymmetry in both joints occurred during the swing phase. Asymmetry present at the ankle during swing (12.3° at 71%GC) could indicate increased dorsiflexion to maximize foot clearance to compensate for the restricted RoM at the knee.

IROD analysis for the unbraced knee during knee-bracing shows a small peak difference during initial swing (−3.1° at 66%GC). However, the braced knee had a much larger peak IROD value during mid-swing (−45.2° at 77%GC). At the ankle, knee-bracing created a small peak value on the unaffected side of the body (−1.5° at 55%GC), and a large peak value on the affected side during terminal stance (−7.5° at 55%GC) and at the end of initial swing (14.7° at 72%GC). Again, these results indicate that the affected side of the body was perturbed more by the bracing. While the hip had no direct bracing, the knee brace created significant peak IROD values at the hip on the affected side during swing (−8.9° at 78%GC), and the hip on the unaffected side during stance (4.5° at 33%GC). This is an indication that both hip joints were used to compensate for the restricted range of motion created by a single knee brace.

SROD analysis showed that ankle-bracing primarily affected the ankles, especially during single limb support (Fig. 3). The greatest peak difference value occurred during terminal stance near the transition to swing (mean ankle difference of −8.2° at 52% of the gait cycle), but a smaller peak value was also detected during initial swing (3.5° at 70%GC). Ankle-bracing did not create significant asymmetries at the knee. However, symmetry of the hip joint was affected by the ankle brace during stance with a peak hip SROD value midway through terminal stance (−3.2° at 38%GC). It is likely that ankle-bracing reduced the subject's ability to generate propulsive force at the joint requiring compensatory motion from the hip for propulsion.

Ankle-braced IROD values indicated that ankle-bracing largely impacts the affected side of the body. Small asymmetries were present in the unbraced ankle during terminal stance (−1.5° at 55%GC), but the asymmetries at the braced ankle during terminal stance were much larger

(−11.5° at 55%GC, Fig. 4). Interestingly, ankle-bracing created significant IROD values for both the affected (−4.7° at 76.6%GC) and unaffected knee joints (−3.3° at 67%GC). This shows that the ankle-bracing is affecting the behavior of the knees during swing, but not in an asymmetric manner. Ankle-bracing had a minimal effect on the IROD values for both hips. This indicates that ankle-bracing increases the asymmetric behavior of the joint pairs, but does not significantly affect the behavior of the individual joints.

Joint angles on the affected side of the body were perturbed more by the bracing than the joints on the unbraced side. This is shown most clearly in the IROD plots of the braced joints (Fig. 4) where IROD values for the unaffected side are small compared to the braced side. The asymmetry shown in the SROD plots (Fig. 3) results from the deviation of the affected side from normative behavior. The similarity between the SROD and braced IROD plots indicates that the joint motion of the unaffected side remains close to the normative behavior, while the braced side is forced to make larger deviations in order to compensate for the perturbation.

4.2. Traditional parameters

As expected, significant differences between univariate range of motion measures for the affected and unaffected joints were observed (Tables 1 and 2). Range of motion parameters indicated that bracing increased asymmetry, such that the maximum range on the affected side of the body was typically reduced, with the exception of the ankle brace's effect on the affected hip joint range of motion, which increased.

Joint range of motion at the ankle, knee and hip and the corresponding symmetry indices indicated that bracing had the greatest effect on the restricted joint (Tables 1 and 2). Subjects also compensated for joint restriction by increasing time spent in single-leg support (SLST) on the unaffected leg. This indicates that the perturbation created by the bracing affects weight acceptance or single limb support (Vaughan et al., 1999). Finally, step width increased significantly during both ankle and knee-bracing, and could be due to an attempt to improve overall stability during perturbation by increasing the base of support.

No difference was seen in step length, but the use of a treadmill during the experiment may have minimized the effect of the bracing on this parameter. Studies have shown that treadmill gait is similar to overground gait (Riley et al., 2007), but the constant treadmill belt speed for each leg could have encouraged subjects to take equal step lengths regardless of the bracing condition.

4.3. Limitations of the study

The modest effect of ankle-bracing on the affected side knee and hip could be the result of increased range of motion of the leg enabled by a convex rocker that was built into the sole of the ankle brace used in this study. During swing, restricting ankle range of motion to the neutral position would have minimal effect on the motion of the knee or hip. However, during stance, when this constraint should create the greatest perturbation, the rocker allowed the shank to smoothly roll over the ankle despite being locked at neutral, resulting in a minimized impact to the knee and hip. Despite this, the ankle brace did result in a perturbation of gait as seen by changes in the pattern of movement at the hip joints. Additionally, increased step width during bracing could potentially be the result of the subjects compensating for the bulk of the brace by using wider steps to ensure that the swing leg moves by the support leg without making contact with the brace, and not because they have increased their base of support for increased stability. Further investigation is needed to address these questions.

5. Conclusions

As expected, bracing at the ankle and knee increased asymmetry in several gait parameters. Bracing decreased the symmetry of paired joint range of motion, increased the subject's step width, and reduced the time subjects spent in single-leg support on the affected leg. Additionally, traditional gait analysis parameters along with the associated symmetry index scores showed that the range of motion of the affected side of the body was smaller than the unaffected counterparts. Overall, knee-bracing created a larger perturbation to gait than ankle bracing. However, traditional parameters failed to identify specific areas of the gait cycle affected by the bracing or quantitatively describe how gait symmetry was affected by bracing in those regions. Symmetry indices did provide a metric to describe the symmetry of the univariate parameters, but did not provide significantly more information than comparisons of the parameters by themselves.

In contrast, our ROD analysis identified regions of significant joint angle asymmetry resulting from braced joints, provided timing and magnitude of the asymmetries, and identified which individual joints were affected by the bracing. SROD analysis showed that ankle-bracing had the greatest effect on the symmetry of the ankle and hip joints during single-leg support, but did not significantly affect the symmetry of the knee. Knee-bracing affected the symmetry of all the joints, and created significant asymmetries during both stance and swing at both the ankle and hip. Finally, IROD analysis showed that bracing had a larger effect on the joints of the braced leg, and that the ankle brace does impact the knee joint but in a symmetric manner. Because SROD and IROD analyses provide a more detailed quantification of the effect on neighboring joints, magnitude, and timing of gait perturbations then traditional parameters alone, this type of analysis should be useful for clinicians to better detect gait impairments and to quantitatively monitor change in gait as a function of recovery.

Conflict of interest statement

None of the authors has a potential conflict of interest (e.g., consultancies, stock ownership, equity interests, patent-licensing arrangements) related to the manuscript or the work it describes.

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