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Effects of Restricted Knee Flexion and Walking Speed on the Vertical Ground Reaction Force During Gait

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The ground reaction force during gait is defined as the force exerted on the foot by the ground. This force is three-dimensional and can be resolved into three components: vertical, fore-aft, and medial-lateral. Normal walking is a complex biomechanical process and, during ambulation, each component of the ground reaction force varies throughout the gait cycle in regard to its magnitude and direction. Many investigators have analyzed one or more components of the ground reaction force during ambulation in both normal, healthy subjects (6,8,12,25) and in individuals with a wide spectrum of pathological conditions (3,4,7,9,11,20,23).

Of the three components of ground reaction force, the vertical component represents what is commonly referred to as the weight-bearing function of the leg. The magnitude of this vertical component includes the force required to continually oppose gravity as well as the force needed to move the body’s center of gravity up and down with each step (15,22). Thus, the vertical ground reaction force varies continually from the instant of initial contact until the foot leaves the supporting surface and commonly has peak magnitudes in excess of a subject’s body weight (9,26). The characteristics of the vertical ground reaction force can be affected by many factors, such as body mass and proportions, walking style, coordination and balance, and, especially, walking speed. Numerous studies have shown that the characteristics of the vertical ground reaction force (such as loading rate, peak force, average force, etc.) are affected by walking speed (1,2) and that it is necessary to control this factor in order to make any meaningful comparisons concerning the vertical ground reaction force across different individuals. Vertical ground reaction forces have been shown to be reliable and repeatable measures of gait (10). Although lower extremity immobilization, including restricted knee flexion, is commonly used in rehabilitation, the effect of angle of knee restriction and walking speed on the vertical ground reaction forces during gait is unclear. Force plate measurements were made on 36 healthy males walking at three different speeds when knee flexion was unrestricted and restricted to both 10 and 25°. Analysis of variance and post hoc analyses showed significant increases in four characteristics of the vertical ground reaction force in the restricted leg and in two characteristics in the unrestricted leg during walking with restricted knee flexion. Loading rate and unloading rate for the restricted leg and peak force for both legs showed significant speed-knee flexion restriction interactions. At the fast walking speed, two significant differences were found between knee flexion restrictions of 10 and 25°. The clinical implications of these findings are that restricted knee flexion during gait may significantly alter the forces applied to both lower limbs.

Key Words: ground reaction forces, knee restriction, gait

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ten desirable to restrict or completely eliminate flexion of the knee in order to allow some healing process to occur following meniscal and ligamentous repair, debridement, and patellar realignment (18). If knee flexion is completely eliminated, the normal shock absorption function of the knee would not be expected to occur and alterations in the vertical ground reaction force are likely to result. Some alterations in the ground reaction force of the unrestricted leg might also be evident. If, however, only a partial restriction of knee flexion is imposed, the knee’s role as a shock absorber at heel strike could be maintained and the vertical ground reaction force may be unaffected. In the case of both partial and total restriction of knee flexion, it is likely that the ground reaction force would be altered during other parts of the gait cycle as the individual tries to compensate for a lack of normal knee flexion; for example, vaulting or circumduction may be used to replace the 60° of knee flexion normally used during swing phase. These “compensatory” gait deviations are likely to be reflected in altered characteristics of the vertical ground reaction force in the leg with restricted flexion as well as in the unrestricted leg. Although several studies have investigated vertical ground reaction forces during normal walking, in persons wearing heels, in amputees, and with functional rehab braces (7,8), there is little or no information concerning the effects of restricting knee flexion. Lage et al (12) investigated the effect of unilateral knee immobilization (brace locked at 0, 10, and 20°) compared with normal free walking (N = 7). Ground reaction force data for both legs were collected at a self-selected walking speed; however, data were not reported as ground reaction force values, but used as input to equations for determining lower limb kinetic measures of power.

The purpose of this study was to measure the effects of restricted knee flexion and walking speed on the vertical ground reaction force during gait. The first experimental hypothesis was that, at three different walking speeds, there is a significant difference in loading rate, unloading rate, peak force, and average value of the vertical ground reaction force for a leg with two ranges of knee flexion restriction vs. no restriction. The second hypothesis was that, at three different walking speeds, there is a significant difference in loading rate, unloading rate, peak force, and average force of the vertical ground reaction force for the unrestricted leg during the same conditions.

METHODS

Subjects

Informed consent to participate in this study was obtained from 36 healthy, male volunteers. All procedures were approved by the Human Subjects Review Committee of the institute. Subjects ranged in age from 19 to 44 years of age (X = 25.7 years), in height from 1.68 to 1.88 m (X = 1.79 m), and in weight from 61.8 to 96.4 kg (X = 76.6 kg). Only males were used to decrease gait variations related to gender (6). Age-related variations were minimized by requiring all subjects to fall between the ages of 18–50 years old (14). Height and weight were such that all subjects fell within the fifth and 95th percentile of the normal population as found in standard anthropomorphic tables (16). Each subject was screened to ensure that there was no history of gait abnormality, lower extremity disorder, or low back disorder. Subjects wore loose-fitting clothes and customary walking shoes.

Design

This investigation used a 3 × 3 two-factor, repeated measures design. Nine separate combinations of the independent variables of walking speed (three levels) and knee flexion restriction (three levels) were tested. The dependent variable, vertical ground reaction force, was recorded for both the restricted and unrestricted leg.

Instrumentation

Walking was done on a 12.19 m × 0.61 m × .083 m level wooden walkway with 1.22-m inclines at each end. Numbered lines, 15.24 cm apart, were placed on each incline to serve as starting position indicators for the subjects. The platform contained a 45.72 cm × 60.96 cm × 8.30 cm force plate offset from the center of the platform so that it covered one-half of the width of the walkway. A black, corrugated, rubber mat covered the platform and force plate. The outline of the force plate was discretely marked with black tape to allow investigators to monitor foot placement, while not attracting the subject’s attention to the force plate. Data for one limb were collected as the subject walked along the walkway and data for the other limb were collected upon the return. The custom-made force plate was constructed of two steel plates, with a Genisco AWU250 load cell (Genisco Technology Corporation, Northridge, CA) secured in each corner. The analog signals from the force plate were amplified by a four-channel bridge amplifier and digitized at a rate of 250 samples/sec/channel with a microcomputer data acquisition system. The force plate had a range of 454.5
kg (1000 lbs) with a resolution of 0.5 kg.

A prefabricated adjustable knee orthosis was used as the method of knee flexion restriction. The knee joint of this device was manufactured with two settings which restrict motion of the orthotic knee joints to both 0 and 15° of flexion from full extension. The orthosis consisted of medial and lateral uprights, each with an injection-molded single axis joint with calf and thigh expansions. The orthosis was applied with two 0.64 cm foam wraps placed over the thigh and calf. The two uprights were placed on the medial and lateral aspects of the leg and adjusted to ensure proper orthosis and knee axis alignment. The uprights were secured with six Velcro® straps, three on the thigh and three on the calf.

Procedure

Before initiating the study, all procedures were approved by the Human Subjects Review Committee of the institution. Measurements of height, weight, and lower extremity length (from the anterior superior iliac spine to the medial malleolus) were taken on each subject. Subject weight was recorded from both the force plate and a standard scale. Each subject was allowed to walk on the walkway several times to accommodate to the surface and to the laboratory area. Following accommodation, subjects were trained to walk at one of the three predetermined walking speeds by keeping pace with an investigator who walked alongside and slightly in front of the subject. Once a subject could consistently maintain the desired walking speed, he was no longer paced. Walking speed was measured by an investigator using a stopwatch and was determined by the time required to travel between two marks. Each mark was placed 2.5 m from the center of the force plate, providing 3.7 m on either end of the platform for acceleration and deceleration.

To avoid alterations in gait patterns, the subject was not specifically instructed to step on the force plate. Instead, the subject’s starting position for each trial was altered to obtain proper foot contact on the force plate. The subject was instructed to keep his head up while walking to minimize any tendency to target the

At the fast walking speed, the unloading rate with knee flexion restricted to 25° was significantly greater than walking with both a free knee and with knee flexion restricted to 10°.

knee flexion restriction was also randomized.

When a testing session required a condition of knee flexion restriction, the knee orthosis was applied and manual goniometric measurements were taken at the anatomical knee joint to document the range of flexion. The arms of the goniometer were aligned laterally with the long axes of the femur and tibia. Concerns about brace migration as a result of walking with the orthosis were addressed by evaluating pre- and post-test manual goniometric measurements on all subjects. The range of motion (ROM) was measured by asking the subject to maximally flex the knee while standing in the orthotic device. A paired t test was used to determine if there was a significant change in the amount of anatomical knee flexion allowed by the device as a result of loosening during testing. The subject then walked on the walkway to become accustomed to the device. Following accommodation, a slow or fast walking condition was selected by the investigator. The subject was then instructed to walk at one of the predetermined walking speeds by keeping pace with an investigator who walked alongside and slightly in front of the subject. Once a subject could consistently maintain the desired walking speed, he was no longer paced. Walking speed was measured by an investigator using a stopwatch and was determined by the time required to travel between two marks. Each mark was placed 2.5 m from the center of the force plate, providing 3.7 m on either end of the platform for acceleration and deceleration.

To avoid alterations in gait patterns, the subject was not specifically instructed to step on the force plate. Instead, the subject’s starting position for each trial was altered to obtain proper foot contact on the force plate. The subject was instructed to keep his head up while walking to minimize any tendency to target the
force plate. To facilitate this head-up position, the subject was instructed to look at an eye-level target posted at each end of the walkway.

The subject walked on the walkway until three acceptable trials for each leg at each condition and speed were recorded. An acceptable trial met the following requirements: 1) the entire foot struck the force plate; 2) no part of the other foot struck the force plate; 3) no targeting of the force plate occurred (subject did not visibly alter his gait pattern to hit the force plate); and 4) the subject walked within ±0.1 m/sec of the required speed. Fifty-four trials were recorded per subject. Trials for one leg occurred with the subject walking one direction and for the opposite leg as the subject returned from the opposite end.

Data Analysis

For each leg and each test condition, the mean of the three trials was calculated for four characteristics of the vertical ground reaction force: loading rate, peak force, average force, and unloading rate (Figure 1). Rate of loading was determined by the time it took for the vertical force to go from 5% to 75% of the subject’s body weight. The value was expressed as body weight/second. Similarly, unloading rate was determined by the time it took for the vertical ground reaction force to go from 75% to 5% of the subject’s body weight and was also expressed in units of body weight/second. Peak force was measured as the highest vertical ground reaction force which occurred anytime during the stance phase and was expressed in percent body weight. No attempt was made to determine whether the peak force occurred in early or late stance. Average force was determined using all the values within the 5% loading and 5% unloading thresholds and was also expressed in percent body weight. To assess the variability of vertical ground reaction force characteristics in each leg, a coefficient of variation was determined for all samples (25).

Separate analyses of variance (ANOVA) were calculated for the leg with restricted knee flexion and for the unrestricted leg to determine the effects of subject variability, walking speed, amount of knee flexion restriction, and any interaction between speed and knee restriction. Post hoc Bonferroni-adjusted pair-wise comparisons were done to further examine significant differences among the various test conditions. In all cases, the level of significance was adjusted to maintain an overall value of \( p < 0.05 \).

RESULTS

Due to technical difficulties, one subject’s data were not used in the statistical analysis. The paired \( t \) test between the pre- and post-test goniometric measurements demonstrated no significant difference at the \( p < 0.05 \) level, indicating no slippage or change of knee ROM secondary to migration. These measurements, however, revealed that the knee flexion restriction device did not limit knee motion as intended. Goniometric measurements of anatomical knee flexion with the knee flexion restriction device set at 0° revealed a mean
range of flexion of 9.6° with a standard deviation of 2.3°. With the orthosis set at 15° of flexion, mean anatomical range of flexion was actually 23.9° with a standard deviation of 5.1°. Based on the goniometer measurements, the three levels of the independent variable of knee flexion restriction were actually free (no restriction or orthotic device), approximately 25° of knee flexion, and approximately 10° of knee flexion rather than the intended free, 15°, and 0°.

Walking speed was found to be a significant main effect for all measures for both legs. Figure 2 shows data from a typical subject qualitatively showing the effects of walking speed and knee flexion restriction. Only ANOVA tables of vertical ground reaction force characteristics are included for which there was a significant interaction present between walking speed and knee flexion restriction (restricted leg: loading rate, unloading rate, and peak force; unrestricted leg: peak force). The average coefficient of variation for all vertical ground reaction force characteristics in both legs was 13.55%.

**Loading Rate**

The ANOVA for the restricted leg demonstrated statistical significance for the main effects of speed and knee flexion restriction and for speed-knee restriction interaction (Table 1). There were significant differences among all walking speeds. For both normal (1.3 m/sec) and fast (1.7 m/sec) walking speeds, post hoc analysis revealed significant differences in loading rate between walking with free knee flexion and walking with knee flexion restricted to both 10 and 25°. For the slow walking speed (0.9 m/sec), there was a significant difference between walking with a free knee and walking with knee flexion restricted to 10° (Figure 3a).

The ANOVA for the unrestricted leg demonstrated statistical significance for the main effects of speed (p = 0.0001) and knee flexion restriction (p = 0.0037). No interaction was found. Post hoc analysis of the main effect of speed revealed significant differences in loading rates across all speeds. No significant differences were found between free walking and walking with either amount of knee flexion restriction (Figure 4a).

**Unloading Rate**

For unloading rate, the ANOVA for the restricted leg demonstrated main effects for speed, knee motion restriction, and an interaction between the two (Table 2). Post hoc analysis showed a significant interaction in unloading rate at the fast walking speed (1.7 m/sec). At this speed, the unloading rate with knee flexion restricted to 25° was significantly greater than walking with both a free knee and with knee flexion restricted to 10°. There was no difference between the free knee and the 10° restriction condition (Figure 3b).

For the unrestricted leg, the only significant finding for unloading rate (p < .001) was a difference due to

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**TABLE 1.** Analysis of variance of loading rate for the leg with knee flexion restriction.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>F</th>
<th>p &gt; F</th>
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<td>9699.1</td>
<td>6.85</td>
<td>0.0001</td>
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<tr>
<td>Knee restriction</td>
<td>2</td>
<td>3673.1</td>
<td>44.08</td>
<td>0.0001</td>
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<tr>
<td>Walking speed</td>
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<td>31992.8</td>
<td>383.96</td>
<td>0.0001</td>
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<tr>
<td>Restriction</td>
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<td>548.6</td>
<td>3.29</td>
<td>0.0117</td>
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<tr>
<td>Error</td>
<td>272</td>
<td>11331.9</td>
<td></td>
<td></td>
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</tbody>
</table>

**TABLE 2.** Analysis of variance of unloading rate for the leg with knee flexion restriction.

<table>
<thead>
<tr>
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<th>df</th>
<th>SS</th>
<th>F</th>
<th>p &gt; F</th>
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</thead>
<tbody>
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<td>0.0001</td>
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<tr>
<td>Walking speed</td>
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<td>331.90</td>
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<tr>
<td>Restriction</td>
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<tr>
<td>Error</td>
<td>272</td>
<td>316.6</td>
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</table>
the three different walking speeds (Figure 4b).

Peak Force

The ANOVA for the restricted leg showed statistical significance for the main effects of walking speed ($p = 0.0001$) and knee flexion restriction ($p = 0.0001$). No speed-knee flexion restriction interaction was demonstrated. Post hoc analysis for the main effect of speed showed significant differences in average force among all speeds. Post hoc analysis for the effect of knee flexion restriction revealed significant differences between walking with free knee flexion and walking with both 10 and 25° of knee flexion restriction at all three walking speeds (Figure 3d).

The ANOVA for the unrestricted leg demonstrated statistical significance for the main effects of speed ($p = 0.0001$) and knee flexion restriction ($p = 0.0001$). No interaction was observed. Post hoc analysis for the effect of speed revealed significant differences in average force among all speeds. Post hoc analysis for the effect of knee restriction demonstrated significant differences between walking with free knee flexion and walking with both 10 and 25° of knee flexion restriction at all three walking speeds (Figure 4d).

DISCUSSION

This study hypothesized significant changes in four characteristics of the vertical ground reaction force due to two different levels of knee flexion restriction. The effects and possible interactions of walking speed were also examined. Positive findings occurred for both levels of knee flexion restriction as well as for walking speed. In the restricted leg, all four vertical ground reaction force characteristics were significantly affected by restriction of knee flexion. In the unrestricted leg, peak force and average force were significantly affected. Therefore, the research hypotheses regarding the effects of knee flexion restriction were accepted. All four vertical ground reaction force charac-
teristics in both legs were significantly affected by walking speed and, therefore, the research hypothesis regarding the effects of speed was also accepted. The finding that speed significantly affects the vertical ground reaction force is in agreement with previous studies (1,2,17). The finding that restricted knee flexion has significant effects on the vertical ground reaction force in both legs is a previously unreported result.

Schuit et al (20) reported an average increase of 4.6% in the peak vertical ground reaction force as a result of installing heel lifts in 18 subjects with leg length discrepancies. Balmaseda et al (3) reported a mean increase of 20% in the peak vertical ground reaction force in healthy volunteers wearing ankle-foot orthoses compared to walking without an orthosis. Carmines et al (4) measured ground reaction forces in subjects with taped ankles and found decreased heel impulses as a result of the taping.

Inferences may be made relative to the work of Lage et al (12), who noted changes in kinetic values for both legs due to knee flexion restriction. Compared with the earlier study, this study reports the vertical ground reaction forces for a larger, homogenous sample size (35 subjects vs. 7), at three walking speeds rather than one, and using an orthosis that allowed motion within a restricted range rather than locking the knee at a fixed angle. In the previous study, significant increases, primarily in ankle and hip mechanical work, were reported early in the gait cycle and during push-off for the braced leg (0 and 20° conditions). The current study found changes in loading rate and peak force of the restricted leg that would appear to correspond to the prior study's increases in work at the hip and ankle during the early portions of the gait cycle, where greater peak moments were reported to have been reached quicker following heel contact for the 0 and 20° braced conditions. Although the previous study reported few changes in the unrestricted limb, citing high intersubject variability, their changes during push-off may correspond to the changes in unloading rate found in the current study. Implications may be that the unrestricted limb was able to compensate for the altered mechanics, although the increased peak forces seen in the current study may be reflective of the previous study's proposed increases in the unrestricted limb due to "vaulting" to clear the restricted limb.

As stated earlier, a normally functioning knee serves as a shock absorber in early stance phase and then assists in a controlled, smooth transition of the center of gravity toward the contralateral leg during the preswing portion of stance phase (21). When knee flexion restriction was imposed, alteration of these normal functions occurred. Increased walking speed tended to accentuate these alterations. In the restricted leg, reduced ability to absorb shock was evident by a higher loading rate. Associated with this increased rate of limb loading, the peak force that was ultimately attained was also increased. Both of these factors combined to produce a significantly higher average force on the leg throughout the entire stance phase. The unloading rate was only affected by restriction of knee flexion at the fast walking speed, possibly because at the slower speeds the subjects' unrestricted leg was able to adequately compensate during the double support phase. In the unrestricted leg, an increased peak force and average force occurred with restriction of knee flexion. Kinematic changes in gait during knee restriction have been reported previously (12). An abnormal shifting of the center of gravity toward the unrestricted side may have occurred in order to increase clearance for the restricted limb during swing phase or there may have been changes in step or stride lengths. Loading and unloading rates in the unrestricted limb were not significantly affected by restriction of knee flexion.

In theory, restricting knee flexion to only the last 15° should not affect normal knee mechanics during early stance phase. Complete restriction of knee flexion, however, could be expected to have an important effect. The results of this study indicate a trend in this direction (Figure 3), but the only significant differences between 25 and 10° of knee flexion restriction were for unloading rate at the fast walking speed and peak force in the unrestricted limb. One reason that more significant differences between the two amounts of knee flexion restriction were not found in this study may be the limitations of the orthosis used for knee flexion restriction. When the orthosis was set at 0°, an average of approximately 10° of flexion was actually allowed at the anatomical knee joint. This range of flexion approximated the nominal 15° normally occurring during early stance phase. An orthosis setting of 15° of flexion actually allowed 25° of flexion at the anatomical knee joint. The findings of lack of the orthotic device to accurately restrict knee motion support the findings of others. Stevenson et al (24) reported up to a 20° increase in dynamic knee ROM while attempting to prevent the last 30° toward terminal extension (braces limited to 30° of full knee flexion). Cawley et al (5) reported between a 6.4 and 18.6° increase in ROM in various braces attempting to limit extension ROM. Even though no significant differences were found, the results of this investigation do indicate a trend that the more knee flexion is restricted, the greater the effects on the vertical ground reaction force.

All ROM measurements were taken statically and perhaps even greater dynamic ranges occurred during gait. The use of an electrogoniometer in future studies could assist in determining these dynamic ranges. This was not an original purpose of this study but arose due to the inves-
tigators concern for ensuring no influence due to brace migration.

Walking speed-knee flexion restriction interaction occurred in the restricted leg for the dependent variables of loading rate, unloading rate, and peak force. As speed increases, more knee flexion is needed during early stance phase. Knee restriction at faster walking speeds led to a significantly increased loading rate. Associated with this increased loading rate, the peak force was also significantly increased with faster walking speeds. Interaction in the unrestricted leg was found in the peak force measurement. When speed is increased, more flexion and quicker movements are required. Therefore, at the faster walking speed, the unrestricted leg was nearing its fullest capacity for movement, allowing less latitude for compensation. It should also be noted that there may be changes in ground reaction forces in the fore-aft and medial-lateral directions with knee immobilization.

Clinical Implications

The findings of this study have several implications for the clinical use of devices intended to restrict knee flexion. When the knee is restricted as a component of a treatment program, gait mechanics are altered. A relationship exists between increased ground reaction force characteristics and mechanical stresses on the limb. Since vertical ground reaction force changes were observed in both legs, this implies that each leg experiences increased stress as the result of the use of a knee flexion restriction device. In some instances, increased stress could be helpful to facilitate bone and cartilage development or repair, such as following fractures. In many other cases, however, a knee flexion restriction device is applied as a protective measure while injured or surgically repaired structures are healing (i.e., following meniscal or ligamentous repair, patellar realignment, etc.). In these circumstances, clinicians might consider secondary methods of decreasing the vertical ground reaction force. For example, a patient might be instructed to walk at slower speeds rather than his or her normal speed or the speed of peers or associates. This study clearly supports other studies showing that walking speed is a major determinant of vertical ground reaction force characteristics (2,17). If treatment of an injury allows a partial range of knee flexion, the use of a restrictive device utilizing this range would seem preferable to using more restrictive immobilization than is necessary. In using any device, however, it is important that the clinician accurately check the actual anatomical joint motion allowed by the device rather than relying on the manufacturer’s preset limits.

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CONCLUSIONS

The results of this study indicate: 1) the characteristics of loading rate, peak force, unloading rate, and average value of the ground reaction force in both limbs were significantly affected by walking speed; 2) in the restricted leg, all four vertical ground reaction force characteristics were significantly affected by knee flexion restriction; 3) in the unrestricted leg, peak and average force were significantly affected by knee flexion restriction; and 4) only at the fast walking speed, and only for unloading rate in the restricted leg and peak force in the unrestricted leg, was there a significant difference between walking with knee flexion restricted to 25° and knee flexion restricted to 10°.

The results of this study are important to clinicians who apply external devices to restrict knee flexion as part of patient treatment. The vertical, weight-bearing component of the ground reaction force in both the restricted and unrestricted legs is significantly affected by application of such a device. Patients should be counseled that walking speed is a
very important factor affecting forces in both legs, especially when normal knee flexion is restricted. In particular, patients should be instructed to limit their walking speed to counteract the increases in mechanical stress that result from walking with restricted knee flexion.

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