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TITLE: Restricted unilateral ankle dorsiflexion movement increases inter-limb vertical force asymmetries in bilateral bodyweight squatting

BRIEF RUNNING HEAD: Effects of Restricted Dorsiflexion on Squats

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Restricted unilateral ankle dorsiflexion movement increases inter-limb vertical force asymmetries in bilateral bodyweight squatting

TITLE: Restricted unilateral ankle dorsiflexion movement increases inter-limb vertical force asymmetries in bilateral bodyweight squatting

ABSTRACT:

The purpose of this study was to investigate the effect of unilateral restrictions in ankle dorsiflexion range of motion (DF-ROM) on inter-limb vertical ground reaction forces (vGRF) asymmetries. Twenty healthy and physically active volunteers (age 23 ± 3 years; height 1.72 ± 0.1m; mass 74.9 ± 20.3 kg) performed three barefoot bodyweight squats (control condition) and with a 10º custom built forefoot wedge under the right foot to artificially imitate ankle DF-ROM restriction (wedge condition). Force data was used to calculate the mean asymmetry index score for the upper descent phase (UDP), lower descent phase (LDP), lower ascent phase (LAP) and upper ascent phase (UAP) during the bilateral squat. Significant differences were found for comparisons for each phase between conditions, with effect sizes ranging between 0.7–1.1. Asymmetry index scores indicated that for all phases, the unrestricted limb in the wedge condition produced greater vGRF. Therefore, inter-limb differences in ankle DF-ROM can cause inter-limb asymmetries in vGRF during bilateral squatting. As such, athletes with asymmetrical squat mechanics should be screened for inter-limb differences in ankle DF-ROM to ascertain whether it is a contributing factor.

KEY WORDS: ankle mobility; inter-limb asymmetries; squat technique

INTRODUCTION

The squat is a fundamental movement skill that as an exercise, engages the ankle, knee and hip joints surrounding musculature (10). It is an essential component of a well-rounded strength and conditioning program and routinely suggested for the development of leg strength (5,38). In addition, it has been used as a screening tool for functional performance (29) and injury risk (6).

Sufficient mobility at the ankle joint must be present in order to fulfill the technical demands for lowering and raising the center of mass vertically (20, 29). This is likely most relevant towards the end phase of the descent during the squat, where restrictions in ankle flexibility may manifest in compensations, as full joint range of motion is exhausted (28). Recently, a large body of research has identified the ankle joint as a primary limiter in driving compensatory strategies in squat mechanics (7,25,26,32). As a result of ankle dorsiflexion range of motion (DF-ROM) limitations, compensations in movement strategies in squatting may develop in order to allow an individual to lower their center of mass and complete the task objective (32). Previously, limitations in ankle DF-ROM of approximately 12° have been shown to inhibit full knee flexion from being accessed during squatting (7,25). As knee flexion is a primary contributor to lowering the athlete’s center of mass (38), other joints must compensate within the kinetic chain to allow for the task to be successfully completed (1,15). Consequently, increased peak knee valgus angle (2, 27) and altered spinal alignment (23) have been identified during squatting where diminished ankle DF-ROM was present.

Asymmetries in ankle DF-ROM appear to be a common finding among healthy and physically active individuals (21,24,34). Previously, Rabin et al. (34) demonstrated that in a sample of male military recruits, a mean inter-limb asymmetry in ankle DF-ROM of 5.8° was present between the dominant and non-dominant limb. Furthermore, 23% of the participants presented inter-limb asymmetries in ankle DF-ROM that exceeded 10° (34). Unilateral ankle DF-ROM restriction, caused by previous injury (35), structural deformities (31) or over-activity of the plantar flexors secondary to functional demands (34), may be a factor that could result in inter-limb asymmetries in force development during a squat. However, the functional consequences of such discrepancies were not discussed and are rarely examined in the literature. A key element of safe bilateral squatting is force generation symmetry between legs. Inter-limb asymmetries in force distribution during squatting have previously been shown to result in technical faults in exercise form (36). Although compensations driven by restrictions in ankle DF-ROM during bilateral squatting has been previously investigated (25,32), few studies have investigated the effects of a unilateral restriction in ankle DF-ROM on inter-limb asymmetries in vertical force production during bilateral squatting. Whether inter-limb asymmetry in ankle DF-ROM of 10°, similar to what was identified for some participants in Rabin et al. (34), is functionally meaningful and has the potential to alter lower extremity loading mechanics during bilateral squatting is at present unknown. Furthermore, as partial range of motion squatting demands less joint displacement throughout the lower extremity relative to deep squatting (11), it may be that unilateral limitations in ankle DF-ROM only impact mechanics during deep squatting. Therefore, the aim of this study was to investigate the influence of a unilateral restriction of ankle DF-ROM on inter-limb vertical ground reaction force (vGRF) asymmetry, during bilateral squatting. The hypothesis for this investigation was a unilateral restriction in ankle DF-ROM would cause asymmetries in vGRF during the body weight bilateral squat.

METHODS

Experimental approach to the problem

Using a crossover study design, this investigation measured inter-limb asymmetries in vGRF during bilateral bodyweight squatting, with and without a forefoot wedge designed to imitate a unilateral limitation in ankle DF-ROM. Subjects reported to the human performance laboratory for one familiarization and one testing session. The familiarization session involved subjects having their ankle DF-ROM measured bilaterally using the weight-bearing lunge test (WBLT) to ensure subjects matched the inclusion criteria. Subjects were then introduced to testing procedures in order to ensure technical competence for both conditions; bilateral bodyweight squatting with a forefoot wedge under the right foot (wedge condition) and bilateral bodyweight squatting with no wedge (control condition). In testing sessions, subjects performed three bilateral bodyweight squats with and without a forefoot wedge, with each foot on a single portable force platform recording vGRF at 1000Hz (Pasco, Roseville, CA, USA).

Subjects

Sample size was determined by *a prior* power analysis in G*power using a target effect size of 0.2, alpha value of 0.05 and statistical power of 0.80, suggesting 12 subjects were required for participation to detect a significant difference between conditions. Twenty physically active men (*n* = 10) and women (*n* = 10) volunteered for this study (age = 23 ± 3 years; height = 1.72 ± 0.1 m; mass = 74.9 ± 20.3 kg). All subjects were deemed to be physically active at a recreational level, defined as performing 30 min of moderate intensity physical activity, at least 3 days of the week for at least six-months prior to testing (27). All subjects reported having previous experience performing bilateral squatting as part of their exercise history. Subjects were excluded if they had a history of lower extremity or spinal surgery (7), were currently experiencing lower limb joint pain at the time of testing (25) or possessed a bilateral difference of <5° in ankle DF-ROM. All tested subjects met the inclusion criteria. Subjects were informed of the risks and benefits associated with testing and completed a pre-exercise questionnaire as well as signing an institutionally approved informed written consent form. Ethical approval was provided by the Institutional Research Ethics Panel.

Procedures

All subjects were instructed to report to test sessions wearing above-knee shorts and appropriate sportswear. For the familiarization session, following the completion of relevant documentation (i.e. informed consent forms and pre-exercise screening questionnaire), subjects had their height and body mass recorded. Subjects then performed the WBLT bilaterally. Using methods previously described (21), subjects began the test by facing a bare wall, with the greater toe of the test leg positioned against the wall. The great toe and the center of the heel were aligned using the marked line on the ground. Subjects were instructed to place the non-test foot behind them, with the heel raised and at a distance that they felt allowed them to maximize their performance on the test. Subjects were asked to keep both hands firmly against the wall throughout to maintain balance. The subjects were then instructed to slowly lunge forward by simultaneously flexing at the ankle, knee and hip on the test leg in an attempt to make contact between the center of the patella and the vertical marked line on the wall. No attempt was made to control trunk alignment or subtalar joint position. Upon successful completion of an attempt, where contact between the patella and the wall was made with no change in heel position relative to the ground, subjects were instructed to move the test foot further away from the wall by approximately 0.5 cm. No restrictions were placed on the number of attempts made by a participant. At the last successful attempt, the distances between the heel and the wall, and the distance between the anterosuperior edge of the patella and the ground were recorded to the nearest 0.1 cm. To measure tibia angle relative to vertical on the lead leg during the WBLT, the trigonometric measurement method (DF ROM = 90- arctan [ground-knee/heel-wall]) was employed for each attempt using the heel-wall and ground-knee distances (21). This procedure was repeated three times, with the mean value from the three attempts used for data analysis.

Subjects were then provided with a demonstration and standardized instructions for the performance of the squat movement. Squat depth was set for each subject as the point whereby the thigh was below parallel to the ground, which was visually determined by the lead investigator. Squat depth was standardized using two stadiometers with a taut string between the adjustable arms. The string was located behind the subjects at a distance that ensured the gluteal musculature contacted the string at the bottom of the descent to provide kinesthetic feedback to subjects regarding when the required range of motion had been achieved during the squat (17). During the familiarization session, the vertical distance of the string from the ground was recorded for each subject so to standardize squat depth and allow for replication during the test session. Following the familiarization session, the subjects returned for the testing session. The same standardized warm-up was performed by all subjects prior to any testing taking place, consisting of a 5 minute jog and dynamic stretches including sumo squats, forward lunges, mountain climbers and leg swings for 10 repetitions.

Bilateral bodyweight squats were performed with the feet approximately shoulder-width apart. Arms were crossed over the chest and eyes fixed on a wall marking to prevent spinal rotation, while allowing the subjects to squat as they normally would, to prevent weight distribution adjustment. Subjects were instructed to squat down until the gluteals touched the string before returning to the standing position. The descent and ascent tempo was controlled using a metronome set to 60 beats per minute to prevent unwanted accelerations (36), with the ascent and descent performed in two seconds for each phase. Subjects performed all squats barefoot to limit the contribution of footwear to squat performance via heel elevation (37). During familiarization for the wedge condition, subjects squatted with the addition of a custom-built 10º incline wooden wedge to replicate ankle DF-ROM asymmetries previously identified in healthy individuals (34). The wedge was placed under the right forefoot so to restrict the angular forward rotation of the tibia, thus imitating a unilateral ankle DF-ROM restriction (25).

For the testing session, subjects performed three squats with and without the forefoot wedge whilst standing with each foot on individual portable force platforms. Each squat was visually monitored in order to ensure the subjects’ gluteals reached the depth identified at the familiarization session (i.e. whether their thigh touched the string) for each repetition (36). Testing order was randomized between conditions for each subject in order to negate any potential learning effects. Subjects were given 30 seconds of recovery between trials.

Data analysis

Raw vGRF data was recorded (Capstone software, Miami, IntraCorp, USA) simultaneously for each limb during each squat. . To identify the four phases of the squat; upper descent phase (UDP), lower descent phase (LDP), lower ascent phase (LAP) and the upper ascent phase (UAP), vGRF data was first summed for both the right and left leg, then using the impulse-momentum relationship, vertical displacement of the center of mass was calculated. The descent phases were characterized by negative velocity while the ascent phases by positive velocity. Upper and lower phases were calculated by identifying the mid-point of each repetition during both the descent and ascent phases for vertical displacement of the center of mass. All force data above the midpoint were used to represent the upper phase of the movement and vice versa for the lower phase.

Once each phase of the squat was identified, inter-limb asymmetries in mean vGRF for each phase were then calculated for all repetitions as described by Bishop et al. (4):

Bilateral Asymmetry Index 1 = (dominant limb – non-dominant limb) / (dominant limb + non-dominant limb) *100

Following this calculation, a positive value was assigned to scores with greater mean vGRF generation by the right leg, while a negative value was assigned to scores with higher mean vGRF generation for the left leg. Asymmetry values for each phase were calculated for each repetition separately, then averaged for each participant and used for further analysis. During the wedge condition, the mass of the wedge was accounted for by subtracted its mass from the right force data for all trials.

Statistical analyses

Descriptive statistics (mean ± standard deviation) were calculated for all variables. Normality was checked using the Shapiro-Wilk test, with all dependent variables being normally distributed. Asymmetry index scores between conditions were examined with paired samples t-test for each phase, with Bonferroni correction for multiple pairwise comparisons. Effect sizes for significant differences were calculated as described by Fritz and Morris (14), and interpreted as follows: 0.0–0.2 *trivial*, 0.2–0.6 *small*, 0.6–1.2 *moderate*, 1.2–2.0 *large*, 2.0–4.0 *very large*, >4.0 *nearly perfect* (18). Statistical significance was set to $p < 0.05$. All statistical procedures were performed using SPSS Statistics (IBM Corp. IBM SPSS Statistics for MacOS, Version 22.0. Armonk, NY, USA).

RESULTS

Descriptive statistics for asymmetry index scores for each phase and both conditions, mean differences and effect sizes are reported in Table 1. A significant difference for all phases between conditions for asymmetry index scores was found, with greater mean vGRF generation for the left (unrestricted) leg in the wedge condition and *moderate* effect sizes for all comparisons (Table 1).

INSERT TABLE 1 HERE

DISCUSSION

The aim of our investigation was to identify the influence of unilateral restriction in ankle DF-ROM on inter-limb vertical ground reaction force production asymmetries during the bilateral bodyweight squat. Our investigation demonstrated that unilateral restrictions for forward rotation of the proximal tibia significantly changed inter-limb asymmetry indexes in all four phases of the squat, by altering the leg producing the highest vGRF during the squat to the unrestricted one.

Previously, inter-limb asymmetries in vGRF have been identified in recreationally trained individuals during the squat movement (12,36). Typical recommendations for reducing inter-limb asymmetries in force production during bilateral squatting are to prescribe strength and balancing exercises (36). However, our findings indicate that unilateral restrictions in ankle DF-ROM are a potential factor in driving these asymmetries in force production during bilateral bodyweight squatting. As differences between limbs in ankle DF-ROM have been shown to exist in both injured (35) and healthy populations (16,24,34), individuals presenting with inter-limb asymmetries in vGRF during the bilateral squat should be screened for inter-limb asymmetries in ankle DF-ROM bilaterally. As weight-bearing measurement techniques have been shown to be more sensitive in detecting asymmetries in ankle DF-ROM (34), it is recommended that the WBLT be employed bilaterally by strength and conditioning professionals, with the between limb difference used to assess an athlete’s functional symmetry profile (19).

Relative to the control condition, all phases of the squat demonstrated significant changes in the inter-limb loading strategy adopted by subjects during the wedge condition. This finding may have implications for other closed-chain activities affected by ankle DF-ROM. Previously, inter-limb asymmetries in force production have been shown in jumping (3) and landing activities (9,39). As these tasks involve similar lower extremity coordination strategies to a partial squat movement (8,10), unilateral restriction in ankle DF-ROM may cause inter-limb asymmetries in force production, based on our findings from the UDP and UAP during bilateral squatting. Although further research is required to support the hypothesis that unilateral restrictions in ankle DF-ROM influence the symmetry profile an athlete demonstrates in bilateral jumping and landing tasks for force propulsion and absorption respectively, our findings show that there is potential for a cause and effect relationship between these variables.

A limitation to this investigation was that individuals were not tested under load during the bilateral squat. As many athletes perform loaded bilateral squats, identifying movement compensations driven by unilateral restrictions in ankle DF-ROM in a loaded squat condition may appear to be more informative to the strength and conditioning professional. Although we expected the unilateral ankle restriction to alter the subject’s squat mechanics, we were unclear as to the compensation strategies that may be employed. To ensure safety for the subjects, we opted for bodyweight squats. It is also worth noting that previous research has shown that asymmetries in bilateral squatting remained unchanged throughout a range of lighter (25%) to heavier (100%) loads relative to an individual’s 1RM barbell back squat (12,36). As it appears that loading does not influence inter-limb asymmetries in vGRF, it is therefore likely that we would have seen the same results regardless of load.

Another potential limitation to the application of our findings was the nature of the restriction in ankle DF-ROM. The wedge was used to artificially restrict ankle DF-

ROM unilaterally and imitate a limitation in ankle DF-ROM using a similar protocol to previous investigations (25,32). Thus, only the acute effects on asymmetries in vGRF were measured. In real-life contexts, unilateral restrictions in ankle DF-ROM that cause compensatory movement strategies to develop in functional patterns, likely transpire over longer periods of time, allowing the athlete to modify and develop their preferred compensation. Whether the acute effects of a unilateral restriction in ankle DF-ROM seen in this investigation are similar to the development of long-term compensations requires further investigation.

Lastly, as part of our investigation we used a forefoot wedge with a 10˚ incline. We based this degree of inclination on previous research that had identified asymmetries in ankle DF-ROM of similar or greater magnitude (34). Whether smaller inter-limb differences in ankle DF-ROM influence asymmetries in vGRF during the bilateral squat is presently unknown. Therefore, further research is required to establish the relationship between inter-limb asymmetries in ankle DF-ROM and squat mechanics.

PRACTICAL APPLICATIONS

This investigation has shown that unilateral restrictions in ankle DF-ROM will influence the symmetry profile an athlete demonstrates during bilateral bodyweight squatting. This presents as greater vertical force being produced by the unrestricted limb relative to the restricted side. Such inter-limb asymmetries in vGRF during bilateral squatting may therefore be detected through a thorough screening process carried out by the strength and conditioning professional. Based on the findings of our investigation, this should include a weight-bearing measurement technique to establish ankle DF-ROM bilaterally. In instances where ankle DF-ROM asymmetries are identified, interventions should be employed that aim to reduce the deficit and integrate the newfound DF-ROM into the squat pattern. This will likely require an individualized approach based on the athlete's coordination profile and their unique response to the intervention (19).

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Table 1. Asymmetry index scores for both conditions and the four squat phases. Data is presented as Mean ± SD. Effect size is presented where differences exist.

Phase	Asymmetry index, % (Mean ± SD)		Mean difference (95% Confidence Interval)	Effect Size
	Wedge condition	Control condition		
UDP	-5.3 ± 9.4	0.5 ± 7.4	5.8* (-8.8 to -2.8)	0.7
LDP	-7.9 ± 10.4	1.7 ± 7.1	9.5* (-13.3 to -5.7)	1.1
LAP	-6.5 ± 12.0	1.6 ± 7.4	8.1* (-12.3 to -3.8)	0.8
UAP	-3.6 ± 8.9	3.0 ± 7.4	6.5* (-10.5 to -2.7)	0.8

Notes: UDP = Upper decent phase; LDP = Lower descent phase; LAP = Lower ascent phase; UAP = Upper ascent phase. * Significant difference between wedge and control condition ($P < 0.0125$).