Improved ankle mobility following a 4-week training program affects landing mechanics: a randomized controlled trial

ABSTRACT

This study examined the effects of a 4-week ankle-mobility intervention on landing mechanics. Twenty participants with restricted ankle dorsiflexion range of motion (DF ROM) were allocated to either a strength training only ($n = 9$) or a strength training and ankle mobility program ($n = 11$). Participants performed a weight-bearing lunge test and bilateral drop-landings before and following the intervention. Normalized peak vertical ground reaction force (vGRF), time to peak vGRF and loading rate were calculated, alongside sagittal-plane initial contact angles, peak angles and sagittal-plane joint displacement for the ankle, knee and hip. Frontal-plane projection angles were also calculated. Following the intervention, only the strength and mobility group improved ankle DF ROM (mean difference = 4.1°, effect size (ES) = 1.00, $P = 0.002$). A one-way analysis of covariance found group effects for ankle joint angle at initial contact ($P = 0.045$), ankle ($P < 0.001$) and hip joint angle at peak flexion ($P = 0.041$), and sagittal-plane ankle ($P < 0.001$) and hip joint displacement ($P = 0.024$) during bilateral drop-landings. Post-hoc analysis revealed that the strength and mobility group landed with greater ankle plantar flexion at initial contact (mean difference = 1.4 ± 2.0˚, ES = 0.46) and ankle dorsiflexion at peak flexion (mean difference = 6.3 ± 2.9˚, ES = 0.74) following the intervention, resulting in greater ankle joint displacement (mean difference = 7.7 ± 4.0˚, ES = 1.00). However, the strength training only group landed with increased peak hip flexion (mean difference = 14.4 ± 11.0˚, ES = 0.70) and hip joint displacement (mean difference = 8.0 ± 6.6˚, ES = 0.44) during post-testing. The findings suggest that changes in landing strategies following the performance of a strength training program are specific to whether restrictions in ankle mobility are considered as part of the intervention.

INTRODUCTION

During landings, ankle dorsiflexion aids in attenuating vertical ground reaction forces (vGRF) (34), whilst facilitating knee and hip flexion via sagittal-plane coupling mechanisms to reduce the impact of landing (31). Restrictions in ankle dorsiflexion range of motion (DF ROM) is recognized as a modifiable injury risk factor for athletes who perform a high volume of landing activities (2). This is likely due to compensations caused by ankle DF ROM restriction during landing tasks, resulting in less effective strategies being used. For example, reduced ankle DF ROM has been shown to limit peak ankle, knee and hip flexion angles (10, 14), whilst increasing peak knee abduction angles during landings (14, 22). Additionally, during landings where individuals with restricted ankle DF ROM demonstrate reduced knee flexion joint displacement, a negative relationship between ankle DF ROM and peak vGRF during bilateral landings has been reported (11). These findings suggest that individuals with ankle DF ROM restrictions land using a stiffer strategy with greater peak knee abduction angles that may result in elevated landing forces.

Increased ankle mobility may improve landing mechanics by increasing sagittal-plane joint displacement at the ankle, knee and hip (10, 11, 14), resulting in reduced peak vGRF (34) and, consequently, diminished injury risk (13). Interestingly, ankle DF ROM can be improved in relatively short time periods as significant gains in ankle DF ROM have been shown in ≤ 4-weeks when adhering to interventions designed to increase flexibility of the ankle plantar flexors (1, 19, 24). Little is known regarding the functional consequences of developing ankle mobility as currently, no studies have investigated the effect of increasing ankle DF ROM on landing mechanics in individuals identified with a mobility restriction at the ankle joint.

In practice, individuals with restrictions in ankle DF ROM will likely be identified during a pre-exercise screening session prior to initiating a strength and conditioning program (18). When deficits in ankle DF ROM are found, a corrective program to restore ankle mobility would be prescribed. This would likely be performed as a supplementary intervention alongside a strength training program designed to develop relevant physical qualities that will improve athletic performance. However, whether a corrective program aimed at restoring ankle mobility results in greater sagittal plane ankle, knee and hip joint displacement, which in turn results in reduced peak vGRF during landing tasks is currently unknown. Therefore, the primary aim of this investigation was to determine the effects of a 4-week ankle mobility program combined with a strength training program on landing mechanics, among participants with pre-established ankle restrictions. We hypothesized that increased ankle mobility would transfer to improved landing mechanics relative to exclusively performing a general strength training program. This would occur as a result of the mobility restriction being reduced, allowing for greater sagittal-plane joint displacement at the ankle, knee and hip, enhancing shock absorption capacity and rendering compensatory strategies obsolete.

METHODS

Experimental Approach to the Problem

For this investigation, a randomized control trial with an independent groups design was used to investigate the efficacy of a 4-week intervention aimed at improving ankle DF ROM and its associated effects on landing mechanics. The independent variable distinguishing groups was the ankle mobility intervention, with participants either performing a strength training and ankle mobility program, or a strength training program exclusively. During an initial screening session, participants were required to perform the overhead squat test and forward arm squat test and were graded in real-time against the criteria rating outlined by Rabin and Kozol (27). Participants with a positive finding for both the overhead squat test *and* forward arm squat test were identified as those demonstrating restricted ankle DF ROM and invited to participate in the study.

Participants that met the inclusion criteria were tested, both before and following the completion of a 4-week intervention, for their performance on the weight-bearing lunge test (WBLT), maximal countermovement jumps (CMJ) and bilateral drop-landings. Participants were randomly assigned to one of two groups: strength and mobility training; or strength training only. Group allocation was performed following the initial screening session via an online randomization system (www.sealedenvelope.com), using stratified randomization, matched for gender, WBLT scores on the right limb and maximal CMJ height. Both groups performed the same strength training program for the lower extremity and trunk musculature, while the strength and mobility group concurrently completed a program using exercises known to improve ankle DF ROM. Post-testing was performed within seven days of completing the intervention for all participants. All test sessions were conducted between 10:00 am and 1:00 pm to control for circadian variation. All participants were informed of the risks associated with the testing and training intervention prior to completing a pre-exercise questionnaire and providing informed written consent. The Institutional Research Ethics Committee provided ethical approval.

Subjects

Using the data from Jeon et al. (19) who examined differences in ankle DF ROM during the WBLT following self-mobilization, we performed a representative analysis using G*power to determine the appropriate sample size. With an alpha of 0.05, calculations indicated that to achieve 80% statistical power, a minimum of eight participants per group were required. All participants were required to meet the following inclusion criteria: (1) between the ages of 18-40; (2) no lower-extremity injury six-months prior to testing; (3) no history of lower-extremity surgery; (4) regularly compete 1-3 times per week in sport events involving landings activities, such as court, racquet or team sports; (5) no previous experience adhering to a structured strength training program (6) present with a positive overhead squat and forward arm squat test during the initial screening session, as outlined by Rabin and Kozol (27). We employed this screen as the overhead squat test forward arm squat test possesses perfect sensitivity (1.00) and fairly high specificity (ranging between 0.84 and 0.88) for detecting individuals with functional limitations in ankle DF ROM (27). Fifty-three participants volunteered for the investigation, with 23 matching the inclusion criteria. To prevent sport training and competition from influencing outcome measures, data collection and the intervention were completed in the competitive off-season for each participant. Eleven participants were randomly assigned to the strength and mobility group (6 males, 5 females; age = 21 ± 1 years, height = 1.74 ± 0.10 m, body mass 75.7 ± 15.4 kg) and 12 participants assigned to the strength training only group (6 males, 6 females; age = 20 ± 1 years, height = 1.72 ± 0.10 m, body mass 71.4 ± 6.8 kg).

Measurements

Testing sessions were structured so that following the recording of height and body mass, ankle DF ROM was measured bilaterally using the WBLT. Participants began the test by facing a bare wall, with the greater toe of the test leg positioned against the wall. The greater toe and the center of the heel were aligned using the marked line on the ground, perpendicular to the wall. Participants were instructed to place the non-test foot behind them, with the heel raised and at a distance that they felt allowed them to maximise their performance on the test. In order to maintain balance, participants were asked to keep both hands firmly against the wall throughout. The participants 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 a vertical marked line on the wall, perpendicular to the line on the ground. Subtalar joint position was maintained by keeping the test foot in the standardized position and ensuring the patella accurately contacted the vertical line. Any elevation of the heel during the test was regarded as a failed attempt and feedback was provided to the participants regarding their inability to prevent the heel from rising. 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, participants were instructed to move the test foot further away from the wall by approximately 0.5 cm. No more than three attempts were allowed at any given distance. At the last successful attempt, the distance between the heel and the wall, and the distance between the base of the patella and the ground were recorded to the nearest 0.1 cm. To determine ankle DF ROM, the trigonometric calculation method (DF ROM = 90- arctan [ground-ground/heel-wall]) was employed for each attempt using the heel-wall and ground-knee distances (17). This procedure was repeated three times for each limb, with the mean value for the right limb across the three attempts used for data analysis. The greatest inter-limb difference during the WBLT across all participants was 1.1˚, with a mean inter-limb difference of $0.3 \pm 0.5°$ and $0.1 \pm 0.4°$ for the strength and mobility and strength training only group, respectively. Intra-rater reliability for this procedure, using a similar population, has previously been reported as excellent (intraclass coefficients (ICC) = 0.98), with a standard error of measurement (SEM) of 0.6° (17). Figure 1 provides an illustration of testing procedures and measurements used for the trigonometric calculation.

INSERT FIGURE 1 HERE

To establish bilateral drop-height for each participant, three maximal CMJ were performed. Following a standardized warm-up, participants were familiarized with performing a CMJ. For the CMJ, participants stood bare foot with a hip-width stance with their hands placed on their hips. Participants were then asked to rapidly descend prior to explosively jumping as high as possible, with no control being placed on the depth or duration of the countermovement. Jump height was measured using photoelectric cells (Optojump System, Microgate, Bolzano, Italy). Three maximal effort CMJs were performed, with 60 s recovery between attempts. The maximum value of the three attempts was used for data analysis and the maximum value from the first test session used to calculate drop height for the bilateral drop-landings for both testing sessions.

Reflective markers were then placed directly onto the participants' skin by the same investigator using the anatomical locations for sagittal plane lower-extremity joint movements and frontal-plane projection angle (FPPA), as outlined by Dingenen et al. (9) and Munro et al. (23), respectively. For sagittal-plane views, reflective markers were placed on the right acromioclavicular joint, greater trochanter, lateral femoral condyle, lateral malleolus and 5th metatarsal head (9). To establish FPPA for the knee joints, reflective markers were placed at the center of the right knee joint (midpoint between the femoral condyles), center of the right ankle joint (midpoint between the malleoli) and on the proximal thigh (midpoint between the anterior superior iliac spine and the knee marker). Midpoints for the knee and ankle were measured with a standard tape measure (Seca 201, Seca, United Kingdom), as described by Munro et al. (23).

Participants were then familiarized with the bilateral drop-landings from a drop height of 150% of maximum CMJ height as the use of this height showed increased reliability and sensitivity in assessing landing kinetics (15) and kinematics (15). For familiarization, participants performed bilateral drop-landings from their individualized drop height and ceased once the participant indicated they were comfortable with the technique and procedure. Bilateral drop-landings were performed with participants standing bare foot with their arms folded across their chest on a height-adjustable platform (to the nearest 0.01 m). All landings were performed barefoot so as to prevent any heel elevation associated with footwear from altering landing mechanics and weakening internal validity (21). Participants were then instructed to step off the platform, leading with the right leg, before immediately bringing the left leg off and alongside the right leg prior to impact with the ground. During this manoeuvre, participants were instructed to ensure that they did not modify the height of the center of mass prior to dropping from the platform (34). For a landing to be deemed successful, participants were required to ensure they landed with each foot simultaneously and in complete contact with the respective portable force platform, which was positioned 0.15 m away from the elevated platform. Each foot landed on a separate portable force platform recording at 1000 Hz (Pasco, Roseville, CA, USA), positioned side-by-side, 0.05 m apart and embedded in custom-built wooden mounts that were level with the force platforms and did not allow any extraneous movement. Full contact with the force platform was visually monitored during landings throughout by the lead investigator, with landings being disregarded where participants failed to either make full contact with the platform or maintain balance (e.g. either taking a step or placing a hand on the ground to prevent falling) upon landing. To ensure participants displayed their natural landing strategy, no instructions were provided regarding heel contact with the ground during the landing phase of the movement and no feedback on landing performance was provided at any point during testing. Participants performed five bilateral-drop landings for data collection, with 60 s recovery between landings.

For 2D video analysis, sagittal and frontal plane joint movements were recorded using three standard digital video cameras sampling at 60 Hz (Panasonic HX-WA30) using the procedures outlined by Payton (26). For sagittal plane joint movements, a camera was positioned 3.5 m from the center of either force platform (15). To record frontal plane kinematics, a camera was placed 3.5 m in front of the center of the force platforms (15). All cameras were placed on a tripod at a height of 0.6 m from the ground.

Intervention

All participants were required to attend three separate training sessions per week for a duration of 4-weeks. Sessions involved performing a strength training program supplemented with either an intervention to increase ankle DF ROM (strength and mobility group) or the strength training program exclusively (strength training only group). The strength training program was designed to develop lower limb and trunk force development capacities (Table 1). For all strengthening exercises, loading was progressed on a session-by-session basis depending on participants' individual responses. This was achieved by maintaining the sets and reps structure for each exercise, while increasing load so that each set was performed 2-3 repetitions from failure whilst maintaining desirable exercise form (36).

INSERT TABLE 1 HERE

The intervention to increase ankle DF ROM was performed by the strength and mobility group on the same days as the strength training program, with exercises completed prior to the dynamic warm-up or following the strength training programme (Table 2). The ankle mobility interventions exercises have previously been shown to increase ankle DF ROM and included self-mobilization (19), self-massage (12), eccentric strength training (1), and static stretching (32). A brief description is provided for each exercise in Table 2. Prescription of all acute variables for the self-mobilization exercise, self-massage and static stretching exercise remained the same throughout the 4-week intervention. The loading for the eccentric strength training exercise was progressed using the same format as described for all other strength exercises.

INSERT TABLE 2 AND FIGURE 2 HERE

Each training session was separated by at least 48-hours and supervised by a UK Strength and Conditioning Association accredited coach. All participants were consistently provided with coaching to improving movement quality for each exercise. Participants were asked to refrain from performing any other strength exercises for the duration of the intervention.

Data Analyses

Raw vGRF data were low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 50 Hz (16). Peak vGRF data were calculated for each leg and normalized to body mass ($N \cdot kg^{-1}$). An independent *t*-test was performed between mean values of peak vGRF for the right and left leg for each participant, with no difference found ($t_{(38)} = -0.847$, $P = 0.402$). Based on these findings, we chose to use force-time data from the right leg to represent kinetic measures of bilateral drop-landing performance. As such, peak vGRF, time to peak vGRF and loading rate were independently calculated for the right leg and used for data collection. For time to peak vGRF to be determined, initial contact was identified as the point that vGRF exceeded 10 N (15). Time to peak vGRF was then calculated as the time difference between initial contact and the time point where peak vGRF occurred. Loading rate was calculated as peak vGRF normalized to body mass divided by time to peak vGRF. Reliability for kinetic measures associated with bilateral drop-landing performance from a drop height equating 150% of CMJ height has previously been reported as nearly perfect (ICC ranging between 0.91 to 0.94), with normalized peak vGRF, time to peak vGRF and loading rate possessing SEM values of $0.23\ N \cdot kg^{-1}$, 0.004 s and $6.7\ N \cdot s^{-1}$, respectively (15).

All video recordings were analyzed with free downloadable software (Kinovea for Windows, Version 0.8.15). For sagittal-plane joint movements, hip flexion, knee flexion and ankle dorsiflexion angles were calculated at initial contact and the point of peak knee flexion for the right limb. These angles were then used to calculate joint displacement for each joint by subtracting the initial contact angle from the peak flexion angle. Initial contact was defined as the frame prior to visual impact between the foot and the ground that led to visual deformation of the foot complex. Peak flexion was identified visually and defined as the frame where no more downward motion occurred at the hip, knee or ankle joints (9). Hip flexion angle was calculated as the angle between a line formed between the acromioclavular joint and the greater trochanter and a line between the greater trochanter and the lateral femoral condyle. Knee flexion angle was calculated as the angle between a line formed between the greater trochanter and the lateral femoral condyle and a line between the lateral femoral condyle and the lateral malleolus. Ankle dorsiflexion angle was calculated as the angle between a line formed between the lateral femoral condyle and the lateral malleolus and a line between the lateral malleolus and the 5th metatarsal head. FPPA was calculated for both sides at the deepest landing position, defined as the frame corresponding to peak knee flexion (23). This angle was calculated as the angle between the line formed between the proximal thigh marker and the knee joint marker and a line between the knee joint marker and the ankle joint marker (23). For hip flexion, knee flexion and ankle dorsiflexion, smaller values represented greater hip flexion, knee flexion and ankle dorsiflexion respectively. For FPPA, values < 180° represented knee valgus and values > 180° representing knee varus.

Reliability for kinematic measures of bilateral-drop landings from a drop height equating to 150% of CMJ height have been previously reported as very large to nearly perfect (ICC ranging between 0.87 to 0.94). SEM for lower extremity joint angles at initial contact and at peak flexion have been reported as ranging between 1.1° to 1.3° and 2.3° to 6.6°, respectively (15). Intra-rater reliability for kinematic measures have been previously reported as nearly perfect for bilateral-drop landings from a drop height equating to 150% of CMJ height (ICC ranging between 0.95 to 0.99), with SEM for joint angles at initial contact and at peak flexion being < 1.5˚ (14).

Statistical Analyses

Descriptive statistics (mean ± standard deviation) were calculated for each kinetic and kinematic variable. The assumption of normality was checked for all dependent variables using the Shapiro-Wilk test. Independent *t*-tests were employed to determine between-group differences for WBLT scores and maximum CMJ height at baseline. A one-way analysis of covariance (ANCOVA) was used to evaluate difference in WLBT and CMJ performance and between-group differences for landing performance following the training intervention. A one-way ANCOVA was chosen as a statistical tool so as to increase power, reduce variability and account for between-group differences at baseline caused by the procedures for group allocation (6, 35). Values for kinetic and kinematic variables associated with landing performance following the training intervention were used as the dependent variable, with baseline values used as the covariate to control for group differences. The α-priori level of significance was set at $P < 0.05$, with a Bonferroni correction applied post-hoc in order to reduce the likelihood of Type I errors. Effect sizes (ES) were calculated for each comparison, with 0.2 being considered *small*, 0.5 *moderate* and 0.8 or greater *large* (5). All statistical tests were performed using SPSS® statistical software package (v.24; SPSS Inc., Chicago, IL, USA).

RESULTS

Three participants from the strength training only group withdrew from the study (for reasons unrelated to the study), resulting in 20 participants completing both testing sessions (strength and mobility, $n = 11$; strength training only, $n = 9$). Attendance for the training sessions was 100% for participants included in the data analysis.

At baseline, there was no difference between groups for CMJ height ($t_{(18)}$ = -0.25, P = 0.282) or WBLT scores ($t_{(18)}$ = 0.26, P = 0.153). However, there was a main effect of group on WBLT at the post intervention time point ($F_{(1,17)}$ = 13.94, P = 0.002) (Figure 3), with the strength and mobility group (mean difference = 4.1 ± 1.4˚, ES = 1.00) demonstrating greater ankle DF ROM than the strength training only group (mean difference = 1.0 ± 2.1˚, ES = 0.18). There was no difference in CMJ height between the groups following the training intervention ($F_{(1,17)}$ = 3.95, P = 0.063) (Figure 4).

INSERT FIGURE 3 AND 4 HERE

Differences for kinematic and kinetic measures of bilateral drop-landing performance before and after the training intervention are presented in Table 3. At initial ground contact a main effect of group was found following the training intervention ($F_{(1,17)}$ = 4.68, P = 0.045), with the strength and mobility group (mean difference = 1.4 ± 2.0˚, ES = 0.46) having less ankle dorsiflexion than the strength training only group (mean difference = 1.0 ± 2.7˚, ES = 0.22). At peak flexion, there was a main effect of group on ankle dorsiflexion ($F_{(1,17)}$ = 19.14, P < 0.001) and hip flexion ($F_{(1,17)}$ = 4.87, P = 0.041). The strength and mobility group (mean difference = 6.3 ± 2.9˚, ES = 0.74) displayed greater ankle dorsiflexion at peak flexion compared to the strength training only group (mean difference = -0.4 ± 3.7˚, ES = 0.06), while the strength training only group showed greater hip flexion at peak flexion (mean difference = 14.4 ± 11.0˚, ES = 0.70) in comparison to the strength and mobility group (mean difference = 4.3 ± 9.0˚, ES = 0.16). Joint displacement for the ankle was significantly greater for the strength and mobility group (mean difference = 7.7 ± 4.0˚, ES = 1.00) than for the strength training only group (mean difference = -1.4˚ ± 3.3˚, ES = 0.23) following the training intervention ($F_{(1,17)}$ = 25.33, P < 0.001). Significant between group-differences were identified post-intervention for hip joint displacement ($F_{(1,17)}$ = 6.13, P = 0.024), with the strength training only group showing greater hip joint displacement (mean difference = 8.0 ± 6.6˚, ES = 0.44) than the strength and mobility group (mean difference = 0.7 ± 6.6˚, ES = 0.03). No other between-group differences were found for kinematic measures associated with bilateral drop-landing performance. No significant between-group differences were found for any kinetic measure following the interventions.

INSERT TABLE 3 HERE

DISCUSSION

The primary aim of this investigation was to identify the effects of a corrective training program on landing mechanics among participants with limited ankle DF ROM. We hypothesized that increasing ankle DF ROM alongside a strength training program would transfer to the execution of a landing task when compared to performing a strength training program alone. Specifically we hypothesised that those receiving an intervention to increase ankle DF ROM and a strength training programme would demonstrate greater sagittal-plane joint displacement at the ankle, knee and hip following the removal of the ankle restriction. The findings, however, failed to support this hypothesis, with changes in landing movement strategies during bilateral drop-landings identified for both groups. Specifically, relative to the strength training only group, increases in ankle DF ROM in the strength and mobility group also resulted in greater ankle plantar flexion at initial ground contact, ankle dorsiflexion at peak flexion, and ankle joint displacement. In contrast, between-group comparisons following the completion of the 4-week program revealed that the strength training only group adapted their coordination strategy by increasing hip flexion angle at the moment of peak flexion, resulting in increased sagittal-plane hip joint displacement (Table 3). As such, it appears that changes in landing strategies following the performance of a strength training program are specific to whether restrictions in ankle mobility are considered as part of the design of the intervention.

To our best knowledge, this is the first investigation to demonstrate that landing mechanics can be altered among individuals who initially present with ankle DF ROM restrictions. Following the intervention, the strength and mobility training group increased peak ankle dorsiflexion and ankle joint displacement during bilateral drop-landings by 6.3 and 7.7˚, respectively. These values were significantly greater than those observed for the strength training only group (-0.4 and 1.4˚, respectively) and exceed the SEM for both of these kinematic variables previously reported using the same procedures (15). Along with contributing to shock absorption at initial ground contact (28), the ankle joint contributes significantly to angular displacement of the knee joint in the sagittal-plane during landings (10, 14). Knee flexion is vital for absorbing shock (34), with reduced knee flexion diminishing knee extensor power output during landings (7). As a result, reduced sagittal-plane knee joint displacement may lead to suboptimal landing strategies (34). Given that the ankle restriction was reduced (i.e. ankle DF ROM increased) following the 4-week intervention, improvements in ankle mobility may facilitate the knee joint's capacity to dissipate vertical forces. In partial support of this suggestion, the strength and mobility group increased their knee flexion at peak flexion by 3.4˚ (Table 3). However, this value is less than the SEM of 3.9˚ previously reported for this variable during bilateral drop-landings using 2D video analysis (15) and should not be interpreted as real change following the intervention.

Furthermore, as peak vGRF did not change for the strength and mobility group beyond the error associated with this measure (16), the modest increase in peak knee flexion angle is unlikely to have provided any functional benefit, as landing forces remained unaffected (Table 3).

Our findings demonstrate that the strength and mobility training group landed with greater ankle plantar flexion at initial ground contact during post-intervention testing. This strategy may be desirable when individuals are attempting to reduce loading associated with a landing task, as 10˚ increases in plantar flexion at initial contact have been shown to decrease peak vGRF and loading rate (28). The same investigation also showed greater plantar flexion at initial contact increased ankle joint contribution to peak support moments. Although we did not measure changes in plantar flexion strength following the intervention, it may be that elevated strength levels following the performance of the single-leg heel drops allowed the ankle to contribute further to energy dissipation. Although this is possible, the mean difference from baseline for ankle joint angle at initial contact for the strength and mobility group following the intervention was 1.4˚ (Table 3). This value is far less than the conscious adjustments in ankle joint alignment used by Rowley and Richards (28), explaining the lack of difference in kinetic measurements following the intervention. This value is also less than the SEM of 1.8˚ previously reported for the testing procedures used (15). Therefore, the between-group difference for ankle alignment at initial contact could be explained by systematic error and should be interpreted with caution.

Another unexpected finding was the changes at the hip joint for the strength training only group. Our findings show that peak hip flexion angle and hip joint displacement increased by

14.4˚ and 8.0˚, respectively. These values were significantly greater than the 4.3˚ increase in peak hip flexion angle and 0.7˚ for sagittal-plane hip joint displacement observed for the strength and mobility group. This finding was surprising, as individuals with functional limitations in ankle DF ROM have been shown to land with reduced peak hip flexion angles and less hip joint displacement when compared to individuals with greater ankle DF ROM (10). However, this may be beneficial for individuals with limited ankle DF ROM to offset the stiffer landing strategy associated with the presence of an ankle restriction. Increasing hip flexion during bilateral landings has been shown to reduce peak vGRF and quadriceps muscle activity, while increasing peak knee flexion angle (4). Previously, recreational athletes with restrictions in ankle DF ROM have been shown to increase peak hip flexion angle during bilateral drop-jumps following the performance of a hip strengthening program (20). As the strength training only group in the current study did not increase ankle DF ROM beyond the error associated with the test (17), it seems that an increased involvement of the hip occurred to the support the knee in attenuating loading during the bilateral drop-landings. This is likely to have occurred because the strength training only group were unable to rely on greater ankle contribution during landings due to the remaining ankle restriction. Thus, the landing strategy of both groups was altered but in different ways. This finding could be of practical significance to individuals with conditions resulting in chronic (less modifiable) restrictions in ankle DF ROM, such as anterior ankle impingement (25). Increased hip flexion during landings is associated with increased hip extensor activity, which acts to resist the elevated external flexion moment (29). As a result, practitioners working with individuals with a non-modifiable ankle restriction should consider that hip-dominant strategies will be adopted and that training interventions placing greater emphasis on development of the hip musculature could help to tolerate the additional loading that is likely to occur.

In this investigation, no between-group differences were found for any kinetic measure of bilateral-drop landing performance following the 4-week training interventions. Furthermore, neither group demonstrated changes outside of the error previously associated with these measures (16). Although a number of reasons may exist for these findings, the most likely explanation is the limited evidence for ankle DF ROM influencing landing forces. At present, only Fong et al. (11) has found a significant correlation between ankle DF ROM and peak vGRF ($r = -0.41$) in healthy participants. Alternatively, numerous studies have shown no significant association between ankle DF ROM and peak vGRF during landing tasks (14, 22, 30). As such, it is likely that other factors influence peak vGRF, such as angular velocity for the knee and hip joints at initial ground contact (33) and the eccentric work performed by the knee and hip extensor musculature (34). Therefore, the findings presented in this study provides further support for the lack of association between ankle DF ROM and peak vGRF.

Ankle DF ROM is related to FPPA during landing tasks, indicating that reduced ankle DF ROM increases knee abduction angle (14, 22). This is suggested to occur as a compensation mechanism for limited ankle DF ROM, whereby increased pronation of the foot complex allows for the continued forward rotation of the proximal tibia (8). However, this finding is not consistently reported, with some studies showing no relationship between ankle DF ROM and knee valgus displacement (11). Here, we found no between-group differences for FPPA following the 4-week intervention, with the strength and mobility group and the strength group increasing FPPA angle (reducing knee valgus) by 5.6˚ and 2.8˚, respectively (Table 3). Both of these values are below the 12.0˚ minimum detectable change value previously reported for this testing procedure (15) and consequently, should not be interpreted as a genuine change in frontal-plane knee alignment. A possible explanation for why ankle DF ROM did not result in significant reductions in knee valgus (increases in FPPA angle) may be that meaningful medial knee displacement was not found for either group at baseline (strength and mobility group = 199.3 ± 22.7˚; strength group = 195.5 ± 13.2˚). Therefore, supplementing a strength training program with an intervention to improve ankle DF ROM, does not appear to reduce peak knee abduction angles during bilateral drop-landings relative to exclusively performing the strength training program in individuals who present with no apparent medial knee displacement.

PRACTICAL APPLICATIONS

This study demonstrated that individuals with a functional restriction in ankle DF ROM were able to change their DF ROM and landing mechanics following a 4-week ankle mobility and strength training program. Specifically, those individuals exposed to a strength *and* mobility training program significantly improved their ankle mobility, resulting in greater ankle dorsiflexion at peak flexion and increased ankle joint displacement when landing relative to those who received a strength training intervention exclusively. Furthermore, these changes in joint alignment exceeded the error associated with the testing procedures. Conversely, the strength training only group compensated for their restriction in ankle DF ROM by employing more hip flexion during landings following the strength training only program. Therefore, Strength and Conditioning professionals working with an individual demonstrating landing mechanics considered to be suboptimal and caused by restricted ankle DF ROM, should consider supplementing the strength training program with exercises to improve ankle mobility. However, in instances where the ankle restriction is non-modifiable, hip extensor strengthening may be appropriate to ensure the individual possesses the necessary strength to cope with the hip-dominant landing strategy.

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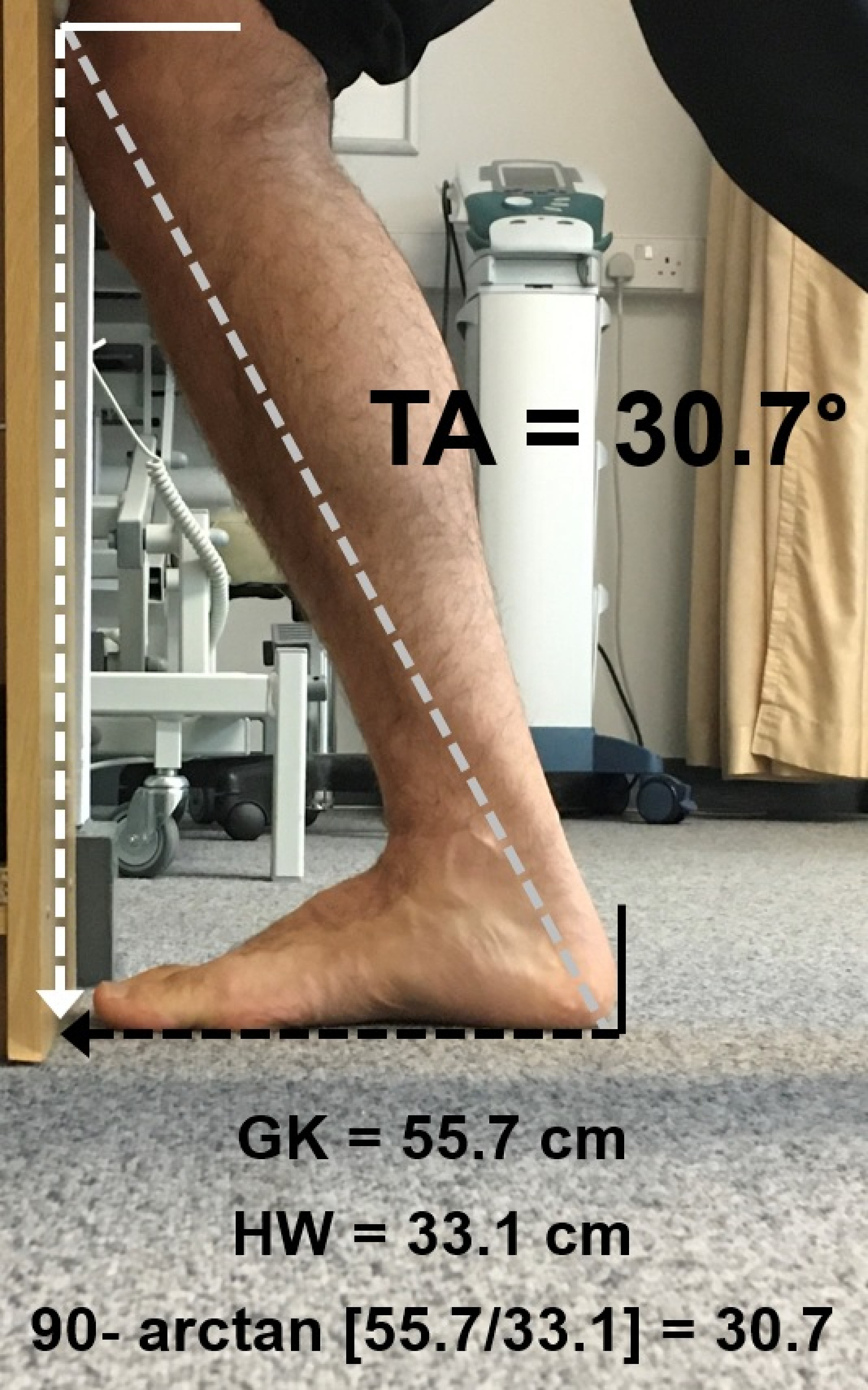
FIGURE LEGEND

Figure 1. Participant performing the weight-bearing lunge test with example calculation. GK= ground-knee distance; HW= heel-wall distance; TA= trigonometric angle.

Figure 2. Exercises used to increase ankle DF ROM for the strength and mobility group. A) Ankle stretch using a strap; B) Ankle plantar flexors self-massage; C) Single-leg heel drop; D) Bent knee ankle plantar flexor stretch.

Figure 3. Weight-bearing lunge test values for both groups (error bars indicate the SD). † indicates a significant between-group difference for post-intervention values (P = 0.002).

Figure 4. Countermovement jump (CMJ) test values for both groups (error bars indicate the SD).


TA = 30.7°
GK = 55.7 cm
HW = 33.1 cm
90- arctan [55.7/33.1] = 30.7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FITNESS

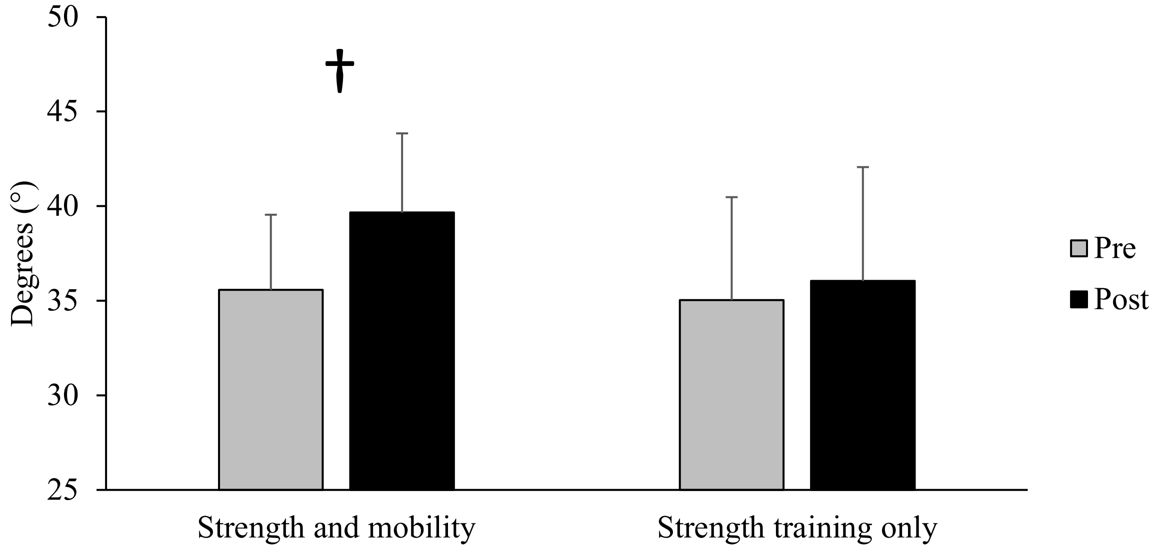

Figure 3. Weight-bearing lunge test values for both groups (error bars indicate the SD). † indicates a significant between-group difference for post-intervention values (*P* = 0.002).

Table 1. Strength-training programme performed by both groups.

Exercise	Sets	Reps	Rest (s)
Dynamic warm-up			
Pole squats	2	6	30
Squats with arms forward	2	10	30
Split squats	2	6	30
Single leg box squats	2	6	30
Countermovement jumps	3	6	120
Session 1			
Pause front squat	3	8-10	120
Single-leg box squat	3	10-12	120
Nordic leg curls	3	6-9	120
Session 2			
Romanian deadlifts	3	10-12	120
Reverse lunges	3	8-10	120
Prone bridge	3	30-60 s	60
Session 3			
Pause front squats	3	8-10	120
Step ups	3	10-12	120
Side bridge	3	30-60 s	60

Table 2. Ankle mobility exercises completed by participants in the strength and mobility training group.

Exercise	Sets	Reps/Duration	Performance
Pre-training session			
Ankle stretch using a strap	3 each leg	20 s	Participant positions their front foot on a 10˚ incline board (length = 0.30 m, width = 0.10 m) and their rear foot behind the front foot in a short lunge position. A non-elastic looped strap (approximately 0.30 m in length) is positioned so the front of the strap is on the anterior aspect of the talus on the front leg and the back of the strap loops over the medial arch of the rear leg. Participants lunge forward until end ankle DF ROM is achieved for the front leg, whilst both feet remain flat on their respective surfaces. This position is held for the prescribed time, with strap tension modulated by manipulating the distance between the feet (19).
Ankle plantar flexors self-massage	3 each leg	30 s	Participant assumes a seated position, with one knee flexed to 90° and the ankle slightly plantar flexed 10˚ using a heel support. From this position, participants massage the plantar flexors using a roller massager. The cadence is 1 s to roll the length of the calf muscles, with intensity set at 7/10 using the rate of perceived pain (12).
Post-training session			
Single-leg heel drop	3 each leg	12-15 reps	The participant places their hands on a wall to maintain balance, whilst standing with their heels hanging off a 0.3 m box. Participants plantar flex at both ankles to their end range, then remove one leg off the box before lowering their centre of mass by fully dorsiflexing the ankle on the weight-bearing limb until the point of maximal perceived stretch. The descent phase is performed at a cadence of 6 s and is self-timed (1). To load the movement, participants hold a load in one hand. Loading is progressed on a session-by-session basis and is achieved by maintaining the sets and reps structure, while increasing load so that each set is performed 2-3 repetitions from failure.
Bent knee ankle	2 each	1 min	The participant places their hands on a wall to maintain balance, whilst standing with one heel (the limb

plantar flexor stretch	leg	being stretched) hanging off a 0.30 m box. The other foot is positioned so the whole of the foot is on the box. With the knee bent to approximately 30˚ on the back leg, the participant dorsiflexes the ankle on the stretched foot until a sensation of a substantial stretch is reported (32). This position is held as prescribed.

Table 3. Pre- and post-intervention differences for both groups for kinematic and kinetic measures associated with landing performance.

Variable	Strength and mobility (n = 11)				Strength only (n = 9)			
	Pre-intervention (Mean ± SD)	Post-intervention (Mean ± SD)	Change in mean (CI)	Effect size	Pre-intervention (Mean ± SD)	Post-intervention (Mean ± SD)	Change in mean (CI)	Effect size
Kinetic variables								
Peak force ($N·kg^{-1}$)	2.07 ± 0.69	2.01 ± 0.69	-0.06 (-0.19, 0.08)	0.08	1.86 ± 0.34	1.88 ± 0.48	0.02 (-0.19, 0.15)	0.05
Time to peak force (s)	0.058 ± 0.018	0.058 ± 0.019	0.000 (-0.003, 0.003)	0.01	0.058 ± 0.010	0.064 ± 0.016	0.006 (-0.018, 0.007)	0.41
Loading rate ($N·s^{-1}$)	41.1 ± 22.9	40.5 ± 23.6	-0.6 (-4.4, 5.6)	0.03	34.6 ± 11.8	34.3 ± 14.5	-0.3 (-6.1, 6.8)	0.02
Initial contact angles								
Ankle (°)*	152.2 ± 2.9	153.6 ± 3.1	1.4 (0.2, 2.5)	0.46	154.1 ± 4.0	153.1 ± 5.2	-1.0 (-2.6, 0.6)	0.22
Knee (°)	169.5 ± 2.3	167.9 ± 2.9	-1.9 (-4.0, 0.2)	0.60	172.0 ± 3.8	168.0 ± 4.1	-3.3 (-6.0, -0.6)	1.00
Hip (°)	161.7 ± 6.4	158.0 ± 6.5	-3.7 (-7.0, -0.4)	0.58	162.8 ± 4.5	156.4 ± 8.5	-6.4 (-11.0, -1.8)	0.94
Peak flexion angles								
Ankle (°)*	108.4 ± 9.0	102.0 ± 8.2	-6.3 (-8.1, -4.6)	0.74	105.8 ± 6.8	106.2 ± 7.3	0.04 (-1.8, 2.6)	0.06
Knee (°)	100.4 ± 16.0	97.0 ± 14.7	-3.4 (-0.1, -6.7)	0.22	99.4 ± 15.6	95.1 ± 15.8	-4.3 (-9.2, 0.7)	0.27
Hip (°)*	96.1 ± 27.0	91.7 ± 28.1	-4.3 (-9.7, 1.0)	0.16	99.4 ± 23.3	85.0 ± 17.7	-14.4 (-7.0, -21.8)	0.70
Frontal plane projection	199.3 ± 22.7	204.9 ± 22.3	5.6 (0.0, 11.2)	0.25	195.5 ± 13.2	198.4 ± 14.1	5.6 (-0.6, 11.8)	0.21
Joint displacement								

Ankle dorsiflexion (°)*	43.9 ± 7.3	51.6 ± 8.1	7.7 (5.4, 10.1)	1.00	48.3 ± 5.6	46.9 ± 6.8	-1.4 (-3.2, 0.4)	0.23
Knee flexion (°)	69.1 ± 15.0	70.9 ± 13.8	1.8 (0.9, 4.5)	0.13	72.6 ± 15.7	72.9 ± 14.8	0.3 (-3.6, 4.2)	0.02
Hip flexion (°)*	65.7 ± 23.6	66.3 ± 23.0	0.7 (-3.4, 4.7)	0.03	63.4 ± 20.2	71.4 ± 16.2	8.0 (4.0, 12.0)	0.44

* = Significant difference between groups.