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original research

Improving Single-Legged–Squat Performance: Comparing 2 Training Methods With Potential Implications for Injury Prevention

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Context: Poor dynamic limb alignment during loading tasks has links to the development of knee injuries, including patellofemoral pain and anterior cruciate ligament injury. Therefore, modalities to improve limb alignment during loading tasks are thought to reduce loading through these structures and potentially prevent injury.

Objective: To compare hip-strengthening and skill-acquisition training to examine if they can improve lower limb biomechanics, potentially preventing injury, and to examine whether changes demonstrated can be maintained after 6 weeks of no practice.

Design: Controlled laboratory study.

Setting: Laboratory.

Patients or Other Participants: A total of 19 recreationally active individuals volunteered, and 17 (9 women: age = 27.9 ± 3.1 years, height = 165.4 ± 8.4 cm, mass = 60.5 ± 9.2 kg; 8 men: age = 30.4 ± 6.4 years, height = 181.4 ± 7.1 cm, mass = 69.8 ± 15.2 kg) completed the study. Nine participants were allocated to a hip-strengthening program; 8, to a skill-acquisition program.

Intervention(s): Participants performed a 6-week training program of either hip strengthening (n = 9) or skill acquisition (n = 8) 3 times per week.

Main Outcome Measure(s): Measurements of clam-exercise strength, hip-abduction strength, frontal-plane projection angle, hip-adduction angle, and a qualitative score were taken at baseline, 6 weeks, and 12 weeks.

Results: We observed improvements in frontal-plane projection angle (strength: $t_8 = 5.344$, $P = .001$; skill: $t_7 = 4.393$, $P = .003$), hip-adduction angle (strength: $t_8 = 3.597$, $P = .007$; skill: $t_7 = 4.722$, $P = .002$), and qualitative score (strength: $t_8 = 3.900$, $P = .005$; skill: $t_7 = 8.283$, $P < .001$) postintervention, which were retained at the 12-week retest in both groups.

Conclusions: A 6-week intervention of either hip-strengthening or skill-acquisition training improved lower limb biomechanics. The changes in biomechanics after skill training were retained at 12 weeks, suggesting a change in motor patterning that could be favorable to longer-term injury prevention.

Key Words: knee, patellofemoral joint, anterior cruciate ligament

Key Points

- A 6-week intervention of strength-based or skill-based training induced meaningful changes in lower limb alignment during a single-legged squat.
- Skill and strength training induced the same improvements, but skill training had the additional benefit of reduced time to complete the intervention.
- Women in the skill-training group consistently demonstrated the greatest changes in frontal-plane projection angle, hip-adduction angle, and qualitative score.
- Learning in the skill-based training group was retained at 12 weeks, suggesting that a true change in motor learning occurred.

Injury to the knee joint is highly prevalent during sports performance.[1] Of particular concern are injuries to the anterior cruciate ligament (ACL) and patellofemoral joint (PFJ), which account for a substantial loss of time from sport.[2] Injuries to these structures can result in the early onset of osteoarthritis and an inability to return to previous activity levels.[3,4] A high proportion of these injuries are incurred through noncontact and overuse mechanisms, suggesting the potential for prevention[1] by changing some of the established modifiable risk factors associated with these injuries.

Dynamic limb alignment and control appear to be substantial factors contributing to such injuries.[5] Poor dynamic alignment presents as a lack of control at the trunk, pelvis, hip, knee, or foot in the frontal or transverse plane.[6] The single-legged squat is a frequently used quick, simple, and cost-effective exercise to analyze dynamic limb alignment.[7] Furthermore, single-legged–squat performance may provide useful insight into a patient's kinematics during higher-load activities, such as jogging and cutting,[8] without subjecting the knee joint to the higher forces associated with these tasks. Researchers using 2-dimensional methods of analyzing single-legged squat have reported good reliability within session and between sessions,[9] with both qualitative and quantitative measures showing good to excellent intratester and intertester reliability.[9,10] In addition, qualitative measures have demonstrated excellent validity compared with 3-dimensional motion kinematics during single-legged squatting and landing.[11]

A common suboptimal behavior demonstrated during loading tasks is dynamic knee valgus, which presents as excessive medial displacement of the knee.[7] Increases in dynamic knee valgus during loading tasks have been reported to increase the risk of injury to the ACL and PFJ.[12,13] Reducing dynamic knee valgus, therefore, is desirable to reduce injury risk and loading of the ACL and PFJ. Injury-prevention programs have resulted in reduced noncontact injury rates for the ACL and PFJ[14,15] and reduced dynamic knee-valgus angles and moments.[16] Key components of training to reduce knee valgus and prevent injury appear to be skill learning and functional strengthening.

Whereas investigators have reported the positive effects of hip-exercise protocols for improving strength and reducing and preventing symptoms,[17,18] research linking these strengthening protocols to functional movement patterns, such as squatting, running, and jump landing, is limited. In 1 study,[19] a hip-strengthening and motor-learning intervention improved strength and single-legged–squat performance but these benefits did not transfer to improved running performance. However, it is not clear whether the changes were due to an increase in strength or motor learning.

Skill acquisition through motor learning is increasingly used during rehabilitation because, in isolation, strength training does not consistently modify the lower limb kinematics and kinetics that are considered "at-risk" behaviors.[7,20] Motor learning through feedback that encourages an internal focus of control has effectively targeted and reduced at-risk biomechanical behaviors that have been associated with increased ACL injury in female athletes.[21] Researchers[22] have indicated that motor learning may be enhanced when expert and self-analysis are combined. This combination has demonstrated decreased ground reaction force and increased knee flexion during jump landing,[22,23] increased hip-abduction angles,[23] and reduced frontal-plane projection angle (FPPA).[24] In addition, changes in biomechanics have been retained at 1-week follow-up, suggesting that a change in motor patterning had occurred and potentially leading to a longer-term reduction in injury risk.[22]

The optimal training method to improve dynamic knee valgus during a single-legged squat is unknown. Skill acquisition and gluteal strengthening have been proposed as 2 methods of improving single-legged–squat performance. In intervention studies, researchers examining the effects of training on reducing knee valgus often use a combination of modalities. As such, it is difficult to establish whether individual modalities can cause a meaningful change in lower limb control. To our knowledge, no investigators have identified whether either modality in isolation can improve single-legged–squat performance. Therefore, the primary purpose of our study was to compare these methods of training to identify whether they correlate with functional improvement during performance of a single-legged squat. The secondary purpose was to identify whether skill learning could be retained after a 6-week period of no practice. We hypothesized that both training groups would improve in all measured movement variables.

Table 1. Group Demographics

Characteristic	Group	
	Strength (n = 9)	Skill (n = 8)
Sex, No.		
Men	4	4
Women	5	4
	Mean ± SD	
Age, y	29.66 ± 4.55	28.38 ± 5.53
Height, cm	174.00 ± 11.24	171.75 ± 11.66
Mass, kg	69.84 ± 15.15	74.86 ± 17.38

METHODS

Participants

Nineteen recreationally active individuals volunteered, and 17 (9 women: age = 27.9 ± 3.1 years, height = 165.4 ± 8.4 cm, mass = 60.5 ± 9.2 kg; 8 men: age = 30.4 ± 6.4 years, height = 181.4 ± 7.1 cm, mass = 69.8 ± 15.2 kg) completed the study. We defined *recreationally active* as participating in 30 minutes of physical activity 3 times each week during the 6 months before the study. Volunteers were excluded if they had a lower limb injury at the time of the study or a history of lower limb surgery. *Lower limb injury* was defined as any injury that prevented normal exercise in the 6 months before testing. All participants provided written informed consent, and the study was approved by the University of Salford Research and Ethics Committee.

Procedures

Participants were block allocated into 2 intervention groups, with the first participant allocated to skill acquisition, the second participant allocated to gluteal strengthening, and so on. Demographics are presented in Table 1. The investigators were not blinded to which group participants were allocated while collecting strength and kinematic data.

Both groups completed 3 training sessions per week for 6 weeks. One session was supervised, and the other 2 sessions were home exercise programs. Video analysis of a single-legged squat using a qualitative-analysis tool for single-legged loading, FPPA, and hip-adduction angle (HADD) took place at baseline assessment, 6 weeks, and 12 weeks. We used a qualitative-analysis tool that was recently designed to identify segmental suboptimal movement patterns and injury risk after single-legged loading (Figure 1). The tool involves dichotomous scoring of the movement strategy occurring in individual body regions (arm, trunk, pelvis, thigh, knee, foot). Scoring for each region is denoted as 0 for an *acceptable strategy* or 1 for an *inappropriate strategy*, giving an overall score from 0 (*best*) to 10 (*worst*). The score was developed from qualitative measures of single-legged–squat performance that have demonstrated good to excellent intratester and intertester reliability[10,25] to include trunk and pelvis motion, which are reported as important factors in altering load and alignment of the lower limb.[25,26] This qualitative scoring system has demonstrated excellent validity when compared with 3-dimensional motion-capture kinematics during single-legged squatting and landing.[11] We measured hip-abduction

Qualitative analysis of single leg loading

Date: **Patient:**

Condition: **Left** **Right** **Bilateral**

QASLS	Task: Single leg squat Single leg step down Single leg hop for dist	Left	Right
Arm strategy	Excessive arm movement to balance		
Trunk alignment	Leaning in any direction		
Pelvic plane	Loss of horizontal plane		
	Excessive tilt or rotation		
Thigh motion	WB thigh moves into hip adduction		
	NWB thigh not held in neutral		
Knee position	Patella pointing towards 2nd toe (noticeable valgus)		
	Patella pointing past inside of foot (significant valgus)		
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeably		
	Total		

Figure 1. Qualitative scoring form. Abbreviations: dist, distance; NWB, non–weight bearing; QASLS, qualitative analysis of single-legged squat; WB, weight bearing.

strength at the same intervals. From 6 to 12 weeks, participants did not pursue any intervention so we could determine whether changes in single-legged–squat performance and hip strength were maintained at 12 weeks. At 6 weeks, participants were instructed to discontinue the intervention, and at 12 weeks, we questioned them to ensure compliance.

Gluteal-Strengthening Program

The gluteal-strengthening program consisted of 4 exercises. Each exercise was performed in 3 sets of 12 repetitions. Exercise selection was guided by a review of the literature that identified which exercises provided the best percentage of maximal voluntary isometric contraction of the gluteus maximus and gluteus medius.[24] We excluded exercises that involved a squatting motion because they might have provided a transferable skill-acquisition element. Side-lying hip abduction and quadruped leg extension were chosen to recruit the gluteus medius and gluteus maximus, respectively. The clam exercise was incorporated because it is generally accepted as a standard exercise for hip strengthening and produces good activity of both the gluteus medius and gluteus maximus.[27] A front stepup was selected as a functional exercise that demonstrated good muscle recruitment.[27] Exercises were progressed individually using a session rating of perceived exertion (RPE) scale.[28] The session RPE scale is a reliable tool (intraclass correlation coefficient = 0.88) for identifying different exercise intensities of resistance training.[28] Participants were instructed to rate their perceived exertion of each exercise at the end of the third set of 12 repetitions. If participants rated their perceived exertion as less than 4 (*somewhat hard*), the exercises were progressed using various strengths of resistance bands, ankle weights, and dumbbells to enable participants to work at an RPE of greater than 4.

Skill-Acquisition Program

Participants assigned to the skill-acquisition group received handouts with instructions on the correct technique for a single-legged squat and pictures of common faults. They performed all single-legged squats in front of a mirror to allow them to view and correct their own techniques. During the first 3 weeks, participants performed the single-legged squat with the contralateral leg touching the floor for balance to allow complete focus on alignment strategies. During weeks 3 to 6, they performed the single-legged squat with the contralateral leg flexed behind them at 90°. Participants performed 3 sets of 12 repetitions to match the step-up component of the gluteal-strengthening program. During the supervised exercise session, we gave participants feedback on performance using predetermined cues.

Single-Legged–Squat Analysis

We analyzed single-legged–squat performance on video using 3 methods: FPPA, HADD, and qualitative score. For FPPA analysis, the same investigator (S.J.D.) placed markers on the lower limb using an established protocol.[7] We measured HADD between a vertical dropped line from the anterior-superior iliac spine and the line from the anterior-superior iliac spine to the center of the knee.[19]

A reference mark for participants was placed exactly 3 m away from a video camera (Excilim EX100; Casio Corp, Dover, NJ) that was mounted at 70 cm on a tripod (Bilora Profilo 75-4; Bilora Nederland, Amersfoort, The Netherlands). All digital video footage was recorded without optical zoom to standardize the camera position among participants. They practiced until they were comfortable with the task. Practice trials allowed the examiner (S.J.D.) to measure knee-flexion angle using a standard goniometer (Jamar E-Z Read; Patterson Medical, Warrenville, IL). The same examiner analyzed each single-legged squat. Participants used the *dominant leg*, which was identified as the lower limb that they would use to kick a ball. We instructed them to stand on the reference mark on the dominant leg with their hands by their sides and facing the video camera. We told them to squat down as far as possible for at least 5 seconds, with a minimum of 45° of knee flexion considered acceptable. They were informed that at 3 seconds, they should be at the lowest point of the squat to reduce the effect of velocity on dynamic alignment and to standardize the test. Participants performed 3 consecutive single-legged squats. After recording, we uploaded the video footage to Quintic (9.03 version 17; Quintic Consultancy Ltd, Sutton Coldfield, West Midlands, United Kingdom), allowing us to analyze it using FPPA, HADD, and qualitative-score assessment. An average score across 3 trials was recorded for video analysis using the FPPA, HADD, and qualitative score. We measured FPPA as the angle between the line from the knee joint to the ankle and the line of the proximal thigh to the knee joint. The FPPA and HADD were analyzed on the digital frame that corresponded with maximal flexion of the knee. The same procedure was repeated for each participant at baseline, 6 weeks, and 12 weeks.

Hip-Abduction Strength Assessment

Assessment of isometric hip-abduction and external-rotation strength was performed with participants in a side-lying clam position on a plinth with both hips flexed to 60°. This position was chosen because it demonstrates the most preferential activation of the gluteus medius and gluteus maximus muscles with low tensor fasciae latae activity.[29,30] We used hip abduction in a side-lying position to assess hip-abductor strength, as it is reported to be the most reliable and valid test position.[31] During both tests, the handheld dynamometer (MicroFET; Hoggan Industries, West Jordan, UT) was positioned 5 cm above the lateral knee-joint line and fixed in place with a strap. The strap removed the limitation of examiner strength on handheld dynamometry.[32] Participants performed a maximal contraction for 5 seconds. Three trials were performed with a 15-second rest between trials. We calculated and recorded the average of the 3 trials for each individual. After the procedure, all strength results were normalized to body weight.

Data Analysis

A repeated-measures factorial analysis of variance (ANOVA) with 3 factors (sex [male, female], group [strength, skill], and time [baseline, 6 weeks, 12 weeks]) was conducted to analyze relationships between the factors and outcome measures (FPPA, HADD, qualitative score, clam strength, hip-abduction strength) during single-legged–squat performance. We used paired-samples *t* tests to evaluate within-group differences in FPPA, HADD, qualitative score, and strength test scores at baseline to 6 weeks, baseline to 12 weeks, and 6 to 12 weeks with a Bonferroni correction ($\alpha = .0166$). Independent-samples *t* tests were performed to identify between-groups and sex differences in FPPA, HADD, qualitative score, and hip strength with a Bonferroni correction ($\alpha = .0166$). Effect size was determined per Cohen d as *small* (d = 0.2), *medium* (d = 0.5), or *large* (d = 0.8). Before testing, we pilot tested all methods with 10 participants (5 men, 5 women) to establish between-sessions reliability. All methods of assessing between-sessions intratester reliability produced excellent reliability scores (Table 2). The α level was set at .05. Statistical analysis was performed using SPSS statistical software (version 21; IBM Corporation, Armonk, NY).

RESULTS

Two participants in the skill group were unable to complete the intervention because of unforeseen circumstances. Therefore, a total of 17 participants completed their respective interventions (strength = 9, skill = 8). Compliance was calculated by dividing the number of training sessions completed by the total number of sessions available and was 92% and 96% in the skill and strength groups, respectively. Results are presented in Table 3 and Figures 2 through 4.

Frontal-Plane Projection Angle

We noted an effect of time on FPPA ($F_{2,22} = 21.776$, $P < .001$, effect size = 0.664). Frontal-plane projection angle was reduced from 0 to 6 weeks ($t_{16} = 7.095$, $P < .001$) and from 0 to 12 weeks ($t_{14} = 4.908$, $P = .001$) but not from 6 to 12 weeks ($t_{14} = –1.347$, $P = .22$). The ANOVA showed a combined effect of sex and time on FPPA ($F_{2,22} = 2.954$, $P = .04$, effect size = 0.191). Men and women had reductions in FPPA from 0 to 6 weeks (men: $t_7 = 3.605$, $P = .009$; women: $t_8 = 6.891$, $P < .001$) and from 0 to 12 weeks (men: $t_6 = 3.708$, $P = .01$; women; $t_7 = 3.176$, $P = .02$), but no changes occurred in either sex from 6 to 12 weeks (men: $t_6 = 2.323$, $P = .06$; women: $t_7 = –2.350$, $P = .051$). We did not observe an effect for group and time combined ($F_{2,22} = 0.194$, $P = .83$, effect size = 0.17). Both groups had reduced FPPAs from 0 to 6 weeks (strength: $t_8 = 5.344$, $P = .001$; skill: $t_7 = 4.393$, $P = .003$) and from 0 to 12 weeks (strength: $t_7 = 3.239$, $P = .01$; skill: $t_6 = 3.956$, $P = .007$), but we observed no difference from 6 to 12 weeks (strength: $t_7 = –0.865$, $P = .42$; skill: $t_6 = –0.976$, $P = .37$). No 3-way interaction was present among time, sex, and group ($F_{2,22} = 0.424$, $P = .66$, effect size = 0.037).

Table 2. Between-Sessions Reliability of Different Measures of Analyzing Performance During Single-Legged–Squat and Strength Measures

Measure	Intraclass Correlation Coefficient	Standard Error of Measure	Smallest Detectable Difference
Frontal-plane projection angle, °	0.93	3.01	8.35
Hip-adduction angle, °	0.92	2.24	6.22
Qualitative score (range, 0–10)	0.91	0.89	2.49
Clam strength (60° hip flexion), % body weight	0.90	3.57	9.90
Side-lying hip abduction, % body weight	0.91	4.93	13.66

Hip-Adduction Angle

Time was the only factor reported for HADD ($F_{2,22} = 19.328$, $P < .001$, effect size = 0.637). Hip-adduction angle was reduced from 0 to 6 weeks ($t_{16} = 5.889$, $P < .001$) and from 0 to 12 weeks ($t_{14} = 5.327$, $P = .001$) but not from 6 to 12 weeks ($t_{14} = –0.409$, $P = .79$). We did not observe an effect for sex and time combined ($F_{2,22} = 0.593$, $P = .56$, effect size = 0.051), for group and time combined ($F_{2,22} = 0.006$, $P = .99$, effect size = 0.001), or a 3-way interaction ($F_{2,22} = 0.515$, $P = .60$, effect size = 0.045) among these factors and HADD. In both groups, HADD was reduced from 0 to 6 weeks (strength: $t_8 = 3.597$, $P = .007$; skill: $t_7 = 4.722$, $P = .002$) and from 0 to 12 weeks (strength: $t_7 = 3.434$, $P = .01$; skill: $t_6 = 3.968$, $P = .007$) but not from 6 to 12 weeks (strength: $t_7 = –0.118$, $P = .91$; skill: $t_6 = –0.564$, $P = .59$).

Qualitative Movement Score

We observed an effect of time on qualitative score ($F_{2,22} = 67.571$, $P < .001$, effect size = 0.860). The qualitative score was reduced from 0 to 6 weeks ($t_{16} = 7.093$, $P < .001$) and from 0 to 12 weeks ($t_{14} = 6.501$, $P < .001$) but not from 6 to 12 weeks ($t_{14} = –1.000$, $P = .34$). We also noted an effect of time and group combined on qualitative score ($F_{2,22} = 7.641$, $P = .02$, effect size = 0.410). A greater reduction in qualitative score occurred for the skill group than the strength group from 0 to 6 weeks (strength: $t_8 = 3.900$, $P = .005$; skill: $t_7 = 8.283$, $P < .001$) and from 0 to

Table 3. Group Characteristics at Baseline and at 6 and 12 Weeks Postintervention

Group	Time			Interval	P Value	95% Confidence Interval
	Baseline	6 wk	12 wk			
Strength training						
Frontal-plane projection angle, °	12.76 ± 4.44	6.25 ± 3.19	7.28 ± 5.10	0–6	.001[a]	(3.71, 9.33)
				6–12	.42	(−4.56, 2.12)
				0–12	.01[a]	(1.54, 9.85)
Hip-adduction angle, °	17.31 ± 3.97	13.34 ± 3.52	13.31 ± 3.21	0–6	.007[a]	(1.43, 6.53)
				6–12	.91	(−2.90, 2.63)
				0–12	.01[a]	(1.34, 7.27)
Qualitative score	4.22 ± 1.30	2.33 ± 1.41	2.38 ± 1.51	0–6	.005[a]	(0.77, 3.01)
				6–12	Test not performed[b]	Test not performed
				0–12	.01[a]	(0.58, 3.17)
Clam strength, % body weight	27.64 ± 5.65	37.04 ± 6.04	34.07 ± 4.52	0–6	<.001[a]	(−13.04, −5.75)
				6–12	.01[a]	(1.08, 5.69)
				0–12	.007[a]	(−10.29, −2.41)
Hip-abduction strength, % body weight	39.94 ± 10.60	44.99 ± 9.17	42.79 ± 9.45	0–6	.02[a]	(−8.81, −1.29)
				6–12	.06	(−0.14, 5.13)
				0–12	.22	(−8.50, 2.34)
Skill training						
Frontal-plane projection angle, °	13.34 ± 4.46	7.12 ± 2.13	8.81 ± 4.22	0–6	.003[a]	(2.87, 9.57)
				6–12	.37	(−5.22, 2.24)
				0–12	.007[a]	(1.76, 7.45)
Hip-adduction angle, °	19.66 ± 2.76	15.12 ± 3.13	14.95 ± 2.57	0–6	.002[a]	(2.27, 6.82)
				6–12	.59	(−2.47, 1.54)
				0–12	.007[a]	(1.67, 7.04)
Qualitative score	5.50 ± 1.31	2.00 ± 1.07	2.00 ± 1.15	0–6	<.001[a]	(2.50, 4.50)
				6–12	.36	(−0.49, 0.21)
				0–12	<.001[a]	(2.52, 4.62)
Clam strength, % body weight	28.56 ± 5.60	32.57 ± 7.88	32.36 ± 7.17	0–6	.046	(−7.98, −0.09)
				6–12	.41	(−1.32, 2.84)
				0–12	.03	(−7.40, 0.44)
Hip-abduction strength, % body weight	37.85 ± 7.60	40.37 ± 7.21	39.40 ± 8.36	0–6	.06	(−5.26, 0.19)
				6–12	.40	(−1.44, 3.13)
				0–12	.26	(−6.20, 2.00)

[a] Indicates a change after Bonferroni correction.
[b] Indicates the same value at weeks 6 and 12, so test was not performed.

12 weeks (strength: $t_7 = 3.416$, $P = .01$; skill: $t_6 = 8.333$, $P < .001$). We did not identify a combined effect for sex and group on qualitative score ($F_{2,22} = 4.844$, $P = .05$, effect size = 0.306). In women, the mean qualitative score was lower for skill training than for strength training at 6 weeks (mean score skill = 1.75, strength = 3) and 12 weeks (mean score skill = 3.25, strength = 2). Conversely, in men, the mean qualitative score was lower for strength training than for skill training at 6 weeks (mean score skill = 2.25, strength = 1.50) and 12 weeks (mean score skill = 2.00, strength = 1.50). We did not observe a 3-way interaction among time, sex, and group for qualitative score ($F_{2,22} = 1.284$, $P = .28$, effect size = 0.105).

Clam Strength

We observed an effect of time on clam strength ($F_{2,22} = 34.742$, $P < .001$, effect size = 0.760). Changes occurred from 0 to 6 weeks ($t_{16} = -5.299$, $P < .001$), 6 to 12 weeks ($t_{14} = 2.994$, $P = .01$), and 0 to 12 weeks ($t_{14} = -4.666$, $P < .001$). In addition, we demonstrated a combined effect of time and sex on clam strength ($F_{2,22} = 7.702$, $P = .003$, effect size = 0.412). We noted a strength change from 0 to 6 weeks for men ($t_7 = -2.902$, $P = .02$) and women ($t_8 = -5.638$, $P = .0001$) and from 0 to 12 weeks for men ($t_6 = -2.580$, $P = .04$) and women ($t_7 = 5.299$, $P = .001$) but noted no difference from 6 to 12 weeks for men ($t_6 = 2.187$, $P = .07$) or women ($t_7 = 2.025$, $P = .08$). We also found an effect of time and group combined on clam strength ($F_{2,22} = 4.943$, $P = .02$, effect size = 0.310). Changes in clam strength occurred in the strength-training group at 0 to 6 weeks ($t_8 = -5.946$, $P < .001$), 6 to 12 weeks ($t_7 = 3.472$, $P = .01$), and 0 to 12 weeks ($t_7 = -3.808$, $P = .007$), but no changes in clam strength occurred in the skill-training group from 0 to 6 weeks ($t_7 = -2.417$, $P = .046$), 6 to 12 weeks ($t_6 = 0.894$, $P = .41$), or 0 to 12 weeks ($t_6 = -2.417$, $P = .03$). We observed no 3-way interaction among clam strength, sex, and group ($F_{2,22} = 0.096$, $P = .91$, effect size = 0.009).

Hip-Abduction Strength

Factorial ANOVA revealed an effect of time on hip-abduction strength ($F_{2,22} = 10.982$, $P < .001$, effect size = 0.501). We noted a change from 0 to 6 weeks ($t_{16} = -5.967$, $P < .001$) but no change from 6 to 12 weeks ($t_{14} = 2.854$, P

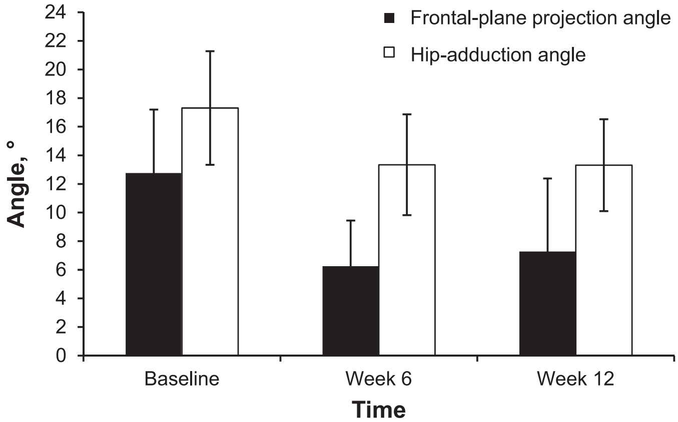

Figure 2. Frontal-plane projection angle and hip-adduction angle at baseline, 6 weeks, and 12 weeks for the strength-training group (mean ± standard deviation).

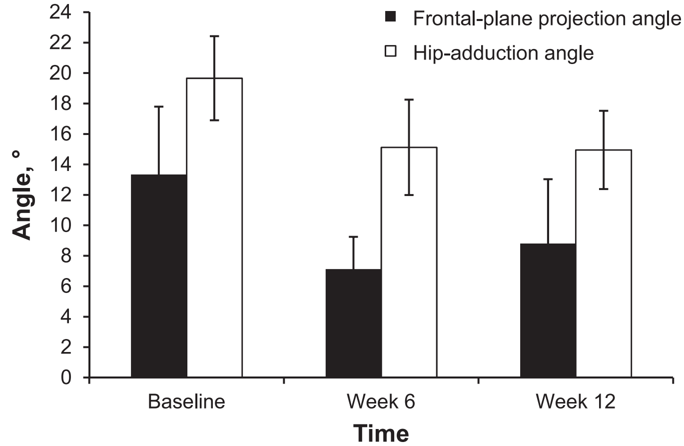

Figure 3. Frontal-plane projection angle and hip-adduction angle at baseline, 6 weeks, and 12 weeks for the skill-training group (mean ± standard deviation).

= .04) or from 0 to 12 weeks ($t_{14} = 2.567$, $P = .04$). The ANOVA also revealed an effect of time and sex combined on hip-abduction strength ($F_{2,22} = 10.974$, $P < .001$, effect size = 0.499). A change occurred in women only from 0 to 6 weeks (men: $t_7 = -1.041$, $P = .33$; women: $t_8 = -5.024$, $P = .001$) and from 0 to 12 weeks (men: $t_6 = 1.678$, $P = .14$; women: $t_7 = -3.742$, $P = .007$). In addition, women maintained their strength at 12 weeks compared with 6 weeks ($t_7 = 0.842$, $P = .43$), but men did not ($t_6 = 2.541$, $P = .04$). We observed no effects for group on hip-abduction strength ($F_{2,22} = 1.500$, $P = .25$, effect size = 0.120). However, only the strength group had a change in hip-abduction strength from 0 to 6 weeks (strength: $t_8 = -3.099$, $P = .02$; skill: $t_7 = -2.196$, $P = .06$), and neither group had a change in hip-abduction strength from 6 to 12 weeks (strength: $t_7 = 2.236$, $P = .06$; skill: $t_6 = 0.906$, $P = .40$) or from 0 to 12 weeks (strength: $t_7 = -1.344$, $P = .22$; skill: $t_6 = -1.251$, $P = .26$). We did not observe a 3-way interaction among hip-abduction strength, sex, and group ($F_{2,22} = 0.194$, $P = .83$, effect size = 0.017).

Independent-samples *t* tests identified no difference among groups for FPPA, HADD, qualitative score, clam-strength tests, or hip-abduction strength tests at any time intervals except for a smaller FPPA for men than women at 12 weeks ($P = .007$; Table 3; Figures 2–4).

DISCUSSION

Most intervention programs used to research changes in lower limb biomechanics with exercise are multimodal, leading to difficulty in establishing which modality produced the meaningful change(s). Therefore, the primary purpose of our study was to examine the effects of skill and strength training on single-legged–squat performance. Both 6-week interventions effectively reduced FPPA, HADD, and qualitative score by more than measurement error. Furthermore, the changes in FPPA, HADD, and qualitative score were maintained at the 12-week retest, although participants received no further training and ceased practice at 6 weeks.

The mean FPPAs for men and women were comparable with those previously reported.[9] The changes in FPPA were greater than the standard error of measure (SEM) but less than the smallest detectable difference (SDD) found during pilot testing. Interestingly, women in the skill group achieved the greatest change and reduced their FPPA by an average of 8.1°, which was close to the SDD of 8.4°. Both groups in this study achieved greater changes in FPPA than in the study of Olson et al,[33] who examined FPPA during a step-down task after a 4-week multimodal neuromuscular-training intervention. Our results add to the multimodal intervention research by demonstrating that both strength and skill training can reduce FPPA. Patients with patellofemoral pain (PFP) and ACL injury have demonstrated greater knee valgus and FPPA during a single-legged squat than healthy control participants.[34,35]

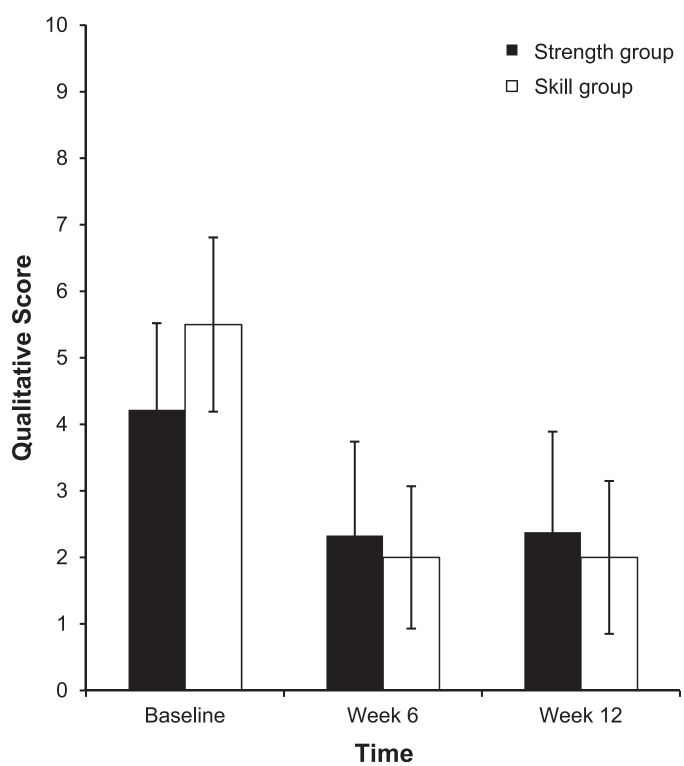

Figure 4. Qualitative score at baseline, 6 weeks, and 12 weeks for the strength-training and skill-training groups (mean ± standard deviation).

The changes in FPPA that we observed might be advantageous in reducing loading through these structures.

We examined the effect of strength and skill programs on HADD. The observed changes were greater than the SEM but less than the SDD noted during pilot testing. Women in the skill group showed the greatest reduction in HADD (5.9°), which was close to the SDD of 6.2°. The changes were maintained at the 12-week stage in both groups. A greater change in HADD (6.7°) during the single-legged squat was demonstrated after a combined 6-week intervention of strengthening and feedback.[19] An increase in hip adduction during loading tasks has been identified in patients with PFP.[36] In addition, a difference of 2.4° to 5.5° in HADD has been reported in patients with PFP compared with healthy control participants during jumping and stair-stepping tasks.[37,38] The increase in hip adduction in these patients can lead to a more lateral positioning of the patella,[39] which over time can lead to increased stress on the lateral compartment of the PFJ and possibly to pain and loss of tissue homeostasis.[40] Therefore, reducing HADD may be important for reducing tissue stress on these structures. In our study, both interventions reduced the HADD by more than measurement error.

In addition to the quantitative measures, qualitative assessments also were performed during the single-legged squat. The postintervention testing revealed mean reductions in qualitative score for both groups (strength = 1.89, skill = 3.50); the changes were greater than the SEM found during pilot testing in both groups and were maintained at the 12-week retest. In addition, the changes in qualitative score in the skill-training group as a whole and in men and women individually were greater than the SDD found during pilot testing for both postintervention tests and were maintained at the 12-week assessment. During single-legged maneuvers, proximal and distal factors can influence loading through the lower limb.[26] When assessing the quality of single-legged loading, the qualitative scoring system takes into account the detrimental effects these factors can have on lower limb loading. In particular, using a qualitative score allows for the analysis of trunk and pelvis motion, which are factors reported to alter lower limb alignment and load.[25,26] Our qualitative scoring results demonstrated that a 6-week intervention of skill or strength training can reduce detrimental injury patterns at multiple motion segments. However, a greater change occurred when individuals participated in skill-based training. The changes in qualitative score were more likely to be greater in the skill group, as they received cueing strategies for these other segments. If the strength-training program had included some trunk-stability training, a greater change might have been seen in this group.

Interestingly, across all measures of single-legged–squat performance, women in the skill group showed the greatest amount of change. Women have higher incidences of ACL and PFP injuries, potentially because of increases in dynamic knee valgus.[34,35] In addition, single-legged–squat performance in female populations is more highly correlated with cutting and landing performance.[8] Therefore, performance of skill-based motor-learning training in programs to improve single-legged–squat performance may have additional beneficial effects on these higher-risk activities and subsequently may reduce injury risk.

Using oral and mirror feedback, we examined skill-acquisition training and its capability to change and retain optimal alignment during single-legged–squat performance. We used a combination of expert and self-analysis, which was shown to enhance motor learning.[22] Whereas it is effective in the short term, the long-term effects are unknown, as researchers[23,24] have examined the effects only immediately postintervention. To ensure that true motor learning has occurred, a retention test is needed, with participants repeating the motor skill after a period of no practice.[41] Onate et al[22] demonstrated that motor-skill learning after feedback can be retained at 1 week. Our observations showed that changes in limb alignment can be maintained up to 6 weeks posttraining. This finding adds to the work of Onate et al[22] indicating that skill-based training can induce changes in long-term motor patterning. The changes in motor patterning would be particularly advantageous for preventing injuries, such as PFP and ACL injuries, that are linked with dynamic knee valgus.[34,35] Skill-based training, therefore, could be used in prevention programs to reduce the chances of these detrimental injuries.

Investigators[19,23] have identified multimodal interventions that can change lower limb biomechanics. These programs often are time consuming to complete, taking from 60 to 90 minutes, 3 times per week. The skill-based training in our study took 10 minutes to complete and was performed 3 times each week. It provided the same benefits as a strength-training program that was performed 3 times each week and took approximately 25 to 30 minutes to complete. Therefore, changes in lower limb biomechanics seem to be achieved quickly and simply with skill-based training.

In our study, the feedback induced an internal focus of control; this adds to findings that internal focus training can effectively change movement.[21] Recently, Wulf[42] demonstrated that instructions using an external focus of control resulted in greater movement efficiency and effectiveness. Given this information, it may be useful for clinicians to adapt their feedback instructions after a skill-acquisition phase to induce an external focus of control. This combined approach to feedback is advocated during rehabilitation after ACL reconstruction to improve motor learning and lessen the secondary injury risk.[43] The change in attentional focus may help individuals move from a phase of acquiring a motor skill to a more autonomous phase that is desirable for sport performance. However, further research is needed to learn how to combine these feedback techniques effectively.

We also found that a 6-week program of gluteal exercises developed strength, with increases of 9.4% and 5.1% body weight for clam and hip-abduction strength, respectively. The changes in hip-abduction strength were greater than those noted by Willy and Davis,[19] who demonstrated a 3% body weight change. Exercises in our study were selected because they have shown high activation levels for the gluteus medius and gluteus maximus, which are important for frontal-plane lower limb alignment.[44] The change in hip-abduction strength observed postintervention further illustrated that these exercises effectively recruit this muscle group. No strength changes were seen in the skill-training group for the hip-abduction or clam-strength test. Therefore, the biomechanical changes in the skill group were due to changes in the central nervous system rather than changes in muscle strength, demonstrating that motor learning had occurred.

Our study had several limitations. We studied asymptomatic, recreationally active individuals, so our results relate only to this population. Individuals with lower limb injury or different activity levels or in different age groups may respond differently. We chose asymptomatic individuals so the results would be applicable to injury-prevention programs. Two-dimensional frontal-plane assessment measures were used because they are easily accessible and reproducible in real-world clinical practice. However, 2-dimensional frontal-plane assessment has its own limitations, as movements through other planes can affect injury. It is possible that we did not include sufficient numbers of participants to power changes. Yet to counteract this, pilot testing the reliability of different measurement tools provided us with SEM and SDD statistics, which increased confidence in the results. These statistics supply greater information about the confidence and importance of the results. We cannot be certain that participants in either group did not continue training in their interventions during weeks 6 to 12, but the chances of this were minimized through proper instruction during weeks 0 to 6 and questioning on return at week 12. Finally, we were not blinded to which group participants were allocated while collecting strength and kinematic data, and this may have introduced bias into the study.

CONCLUSIONS

Most researchers use multiple interventions within their training programs; therefore, it is difficult to identify whether different interventions in isolation can change biomechanics. We demonstrated that a 6-week intervention of strength-based or skill-based training can induce meaningful changes in lower limb alignment during a single-legged squat. Across all measured outcomes, skill training induced the same improvements as strength training, with the additional benefit of reduced time to complete the intervention. Women in the skill-training group consistently demonstrated the greatest and most important changes in FPPA, HADD, and qualitative score. Given the higher incidence of injury in females, these findings may have implications for injury-prevention programs in this population. In addition, another important finding of our study was that, after a period of skill training, retention of learning was maintained 6 weeks postintervention, suggesting that a true change in motor learning had occurred.

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