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Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction

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Abstract The hamstrings musculature is a vital component of an intricate dynamic knee joint restraint mechanism. However, there is evidence based on research studies suggesting potential deficits to this complex mechanism due to donor site morbidity resulting from harvest of the ipsilateral semitendinosus and gracilis autograft (ISGA) for anterior cruciate ligament reconstruction (ACLR). The purpose of this retrospective research study was to investigate the effects of ISGA ACLR on neuromuscular and biomechanical performance during a single-leg vertical drop landing (VDL), a functional task and associated mechanism of anterior cruciate ligament disruption during physical activity. Fourteen physically active participants 22.5 ± 4.1 years of age and 21.4 ± 10.7 months post ISGA ACLR underwent bilateral neuromuscular, biomechanical and isokinetic strength and endurance evaluations matched to 14 control participants by sex, age, height and mass. Kinetic and kinematic data was obtained with 3-D motion analyses utilizing inverse dynamics while performing single-leg VDLs from a height of 30 cm. Integrated surface electromyography (SEMG) assessments of the quadriceps, hamstrings and gastrocnemius musculature were also conducted. Additionally, knee joint flexion strength (60° s^{-1}) and endurance (240° s^{-1}) measurements were tested via isokinetic dynamometry. No significant differences existed in hip and net summated extensor moments within or between groups. The ISGA ACLR participants recorded significantly decreased peak vertical ground reaction force (VGRF) landing upon the involved lower extremity compared to uninvolved ($P = 0.028$) and matched ($P < 0.0001$) controls. Participants having undergone ISGA ACLR also displayed greater peak hip joint flexion angles landing upon the involved lower extremity compared to uninvolved ($P = 0.020$) and matched ($P = 0.026$) controls at initial ground contact. The ISGA ACLR group furthermore exhibited increased peak hip joint flexion angles landing upon the involved lower extremity compared to uninvolved ($P = 0.019$) and matched ($P = 0.007$) controls at peak VGRF. Moreover, ISGA ALCR participants demonstrated greater peak knee ($P = 0.005$) and ankle ($P = 0.017$) joint flexion angles when landing upon the involved lower extremity compared to the matched control at peak VGRF. The ISGA ACLR group produced significantly greater reactive muscle activation of the vastus medialis ($P = 0.013$), vastus lateralis ($P = 0.008$) and medial hamstrings ($P = 0.024$) in the involved lower extremity compared to the matched control. The ISGA ACLR participants also exhibited greater preparatory ($P = 0.033$) and reactive ($P = 0.022$) co-contraction muscle activity of the quadriceps and hamstrings landing upon the involved lower extremity compared to the matched control. In addition, the

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ISGA ACLR group produced significantly less preparatory ($P = 0.005$) and reactive ($P = 0.010$) muscle activation of the gastrocnemius in the involved lower extremity compared to the uninvolved control. No significant differences were present in hamstrings muscular strength and endurance. Harvest of the ISGA for purposes of ACLR does not appear to result in significant neuromuscular, biomechanical or strength and endurance deficiencies due to donor site morbidity. However, it is evident that this specific population exhibits unique neuromuscular and biomechanical adaptations aimed to stabilize the knee previously subjected to ACL trauma and safeguard the ISGA ACLR joint. Co-contraction of quadriceps and hamstrings as well as inhibition of gastrocnemius muscle activation may serve to moderate excessive loads exposed to the intra-articular ISGA during single-leg VDLs. Furthermore, greater muscle activation of the hamstrings in conjunction with increased peak hip, knee and ankle joint flexion angles may assist in enhancing acceptance of VGRF transferred through the kinetic chain following single-leg VDLs.

Keywords Anterior cruciate ligament · Landing · Electromyography · Biomechanics · Rehabilitation

Introduction

A substantial rate of non-contact anterior cruciate ligament (ACL) tears have been linked to landing activities [20, 31, 36, 38, 39]. The functional role of the lower extremity during landing is to efficiently accept, dissipate and transmit vertical ground reactions force (VGRF) [14, 17, 18]. Injury to the ACL can compromise this function. Research studies have demonstrated that only one-third of ACL deficient (ACLD) recreational athletes are capable of adequately compensating for alterations in knee joint stability to permit strenuous physical activity [38, 39]. Due to the low percentage of ACLD individuals adept in successfully incorporating coping mechanisms to the injury, many undergo ACL reconstruction (ACLR). By restoring joint stability and functional performance of the knee, ACLR attempts to prevent the potential onset of related degenerative pathology [1, 9, 33, 45].

Clinical recovery following ACLR is dependent upon genetic cellular mechanisms of repair in addition to the specificities of reconstruction [23, 30, 42, 46]. Concerns regarding ACLR include graft harvest, in particular the rate and quality of repair, as well as functional adaptations arising from injury inflicted upon the donor site [3, 10, 15, 25, 28, 42]. Research studies have suggested autograft ACLR to induce significant muscular strength and endurance deficiencies as a result of tissue harvest [4, 19, 26, 34, 52, 56, 57].

Ipsilateral bone-patellar tendon-bone autograft (IBPTBA) harvest has shown to affect quadriceps muscular strength [26, 52, 56] and impose a consequent knee extensor moment deficit upon the joint [19, 42]. A research study assessing neuromuscular performance of the knee post IBPTBA ACLR revealed significant quadriceps deficits with latencies in reactive recruitment to passive joint perturbation [56]. Further investigation involving lower extremity compensations following ACLR revealed IBPTBA harvest results in performance deficits during functional tasks [19]. More importantly following a vertical jump landing, the knee and net summated extensor moments (hip + knee + ankle) of IBPTBA ACLR lower extremities were observed to be significantly less than that of controls [19]. These findings suggest potential exposure of the intra-articular graft and related knee joint anatomy to further injury as the result of inefficient attenuation of impact [19] or consequent limb collapse from insufficient knee and summated extensor moments [52].

Advocates of the ipsilateral semitendinosus and gracilis autograft (ISGA) cite avoiding trauma to the knee joint extensor mechanism associated with IBPTBA ACLR as a prime advantage of this alternative harvest [2, 4, 10, 45]. Biomechanical experimentation of tensile properties between the two grafts has also established the semitendinosus and gracilis to fail at higher loads [53]. However, harvest of ISGA has shown to yield weakness of the hamstrings musculature in generating knee joint flexion [4, 26, 34, 57] and internal tibial rotation [51]. Due to the bi-articular function of hamstrings, these findings implicate potential insufficiency of the musculature in generating a hip extensor moment [26]. Other potential complications noted after harvesting the ISGA include lesions to the saphenous nerve and rupture of tendons inserting into the pes anserine complex [51]. Donor site morbidity following ISGA harvest also causes inquiry in regards to compromising the synergistic role of hamstrings musculature and ACL in preventing excessive anterior tibial shear forces (ATSFs). This practice in autograft ACLR raises concern from theoretical and clinical perspectives in regards to compromising the dynamic restraint mechanism of the knee joint.

The purpose of this research study was to investigate the effects of ISGA ACLR on neuromuscular and biomechanical performance during a single-leg vertical drop landing (VDL). This functional task has been associated with disruption of the ACL during physical activity [55]. Experimental objectives included assessment of lower extremity neuromuscular and biomechanical profiles as well as hamstrings muscular strength and endurance. The data collected aims to recognize advantages and drawbacks of using the ISGA in ACLR as well as aid the advancement of surgical and rehabilitation techniques specific to this procedure.

It was hypothesized donor site morbidity consequent to ISGA ACLR would result in hamstrings strength and endurance deficits, suggesting insufficiency in restricting ATSFs. As a result of hamstrings muscular deficits, an additional hypothesis stated ISGA harvest lessens the donor site musculature's capacity in generating a hip extensor moment. This would propose susceptibility to limb collapse following a single-leg VDL. It was also hypothesized harvest of the ISGA yields ensuing neuromuscular deficiencies causing diminished reactive recruitment of the hamstrings to dynamic knee joint perturbation. Further hypotheses asserted that reduced muscle activation of the hamstrings would give way to amplified VGRF transmitted to the knee joint. Consequent increased VGRFs may indicate exacerbation of ATSFs, which would potentially prove detrimental to the integrity of the reconstructed knee joint.

Materials and methods

A true posttest-only control group experimental design was utilized for this research study. The sequence of testing the uninvolved and involved lower extremities was randomized to prevent an order effect [19]. Prior to participation in the research study all participants completed a written questionnaire and provided written informed consent in accordance with the university's Institutional Review Board.

Participant demographics

Fourteen recreationally active athletes 22.5 ± 4.1 years of age who underwent ISGA ACLR 21.4 ± 10.7 months prior, barring associated ligamentous or meniscal pathology to the involved knee joint were recruited for this research study. The ISGA ACLR participants underwent analogous orthopaedic surgical procedures by sports medicine specialists and co-investigators (FHF, CDH). The ISGA ACLR participants possessed no history of traumatic injury to the hip or ankle joints of the involved lower extremity and had no account of traumatic injury to the contra-lateral uninvolved limb. The ISGA ACLR group furthermore followed equivalent postoperative treatment protocols at the identical center for sports medicine under the supervision of sports rehabilitation specialists. Control participants matched by gender, age, height and mass had no history of traumatic injury to the lower extremities. The healthy contra-lateral uninvolved lower extremities, serving as internal controls, and matched controls were utilized for comparative analyses. Complete participant demographics appear in Table 1.

Recreationally active was defined as individuals engaging in moderate physical activity with a minimum frequency of 3 days per week, 30 min in duration over a 6-month period. Participants assigned to the ISGA ACLR group were referred to this research study by co-investigators (FHF, CDH).

Table 1 Participant demographics

	ISGA ACLR group	Control group	*P* value
Participants	14	14	
Sex (male/female)	5/9	5/9	
Age (years)	22.5 ± 4.05	22.8 ± 3.5	0.421
Height (m)	1.66 ± 0.070	1.67 ± 0.087	0.442
Mass (kg)	68.4 ± 14.0	65.4 ± 13.3	0.287

An independent *t* test was performed to insure no significant differences existed between ISGA ACLR and control groups

Values are mean ± SD

Biomechanical analyses

Kinetic and kinematic analyses were performed utilizing the Peak Motus System (Peak Performance Technologies, Inc., Englewood, CO, USA) composed of six coupled infrared cameras (Pulnix Industrial Product Division, Sunnyvale, CA, USA) capturing data at a frequency of 120 Hz and computer system with accompanying Peak Motus analyzing software. Biomechanical evaluation further incorporated sampling GRFs at a frequency of 1,200 Hz upon impact subsequent to single-leg VDLs via a mobile multicomponent Kistler 9286A force-plate (Kistler Instrument Corp., Amherst, NY, USA) installed flush within the floor. The Peak Motus System was calibrated to manufacturers specifications with supplied devices before data collection. Prior to motion analyses, bilateral linear and circumferential anthropometric measurements of participants were recorded. Anatomical segments measured include body mass, height, anterior superior iliac spine (ASIS) breadth, thigh, shank and foot length, mid-thigh and shank circumference, knee diameter, malleolus height and width as well as foot breadth. Seventeen reflective markers (diameter of 0.025 m) were used as anatomic surface markers with thigh and shank markers attached to the end of a 0.09 m-long wand. Hip, knee and ankle markers were affixed to the skin via double-sided adhesive tape, with thigh and shank wands secured to the lower extremity by elastic straps. Reflective markers were placed on the following anatomic landmarks bilaterally utilizing the technique established by Kadaba et al. [50] as specified by the manufacturer; ASIS, sacrum, lateral thigh and shank, lateral knee joint line, lateral malleolus, posterior calcaneus and head of the second metatarsal (Fig. 1). A research study found the Peak Motus System produced less than

Fig. 1 Reflective marker orientation for 3-D motion analyses (posterior calcaneus and sacral markers not shown)

Fig. 2 Participant performing a vertical drop landing at initial ground contact

2 mm root-mean-square (RMS) errors when measuring fully visible displacing reflective surface markers, and less than 1 mm RMS errors when measuring stationary reflective surface markers [41]. We established accuracy of the Peak Motus System within our research laboratory to produce errors of less than 1° in calculation of angles. Comparing known coordinates and angles of a rigid object in space to calculations of coordinates and angles recorded by the Peak Motus System completed this. Colby et al. [8] have established reliability of force-plate assessments in measuring VGRFs and lower limb dysfunction.

Participants were given a verbal description and visual demonstration of the single-leg VDL task prior to testing. Standing erect upon only the lower extremity being tested with the foot in neutral position, participants stepped off a 30 cm high platform placed 11 cm from the edge of the force-plate. Participants were instructed to land in the center of the force-plate on the lower extremity being tested only. To control for countermovement, participants were restricted to perform VDLs with hands upon hips and the contra-lateral knee joint flexed to 90°. It was also stressed that the non-tested shank segment did not come into contact with the tested lower extremity. This aimed at limiting horizontal displacement and enabled the participant to land with a more vertical approach. Following a verbal cue, participants dropped off the platform and landed upon the force-plate. Participants performed three practice trials followed by three test trials. Trials were considered valid if participants successfully landed with proper foot placement upon the force-plate and maintained equilibrium upon the lower extremity being tested only. No further cues or instructions were addressed to the participants that might confound performance.

Motion analyses focused upon assessments of hip and net summated extensor moments as well as peak hip, knee and ankle joint flexion angles. Raw kinematic data were filtered and processed via Peak Motus software, which uses a fourth-order zero-lag Butterworth digital filter with a cut-off frequency of 6 Hz. Raw kinetic (GRFs) data were filtered and processed via Peak Motus software using a fourth-order Butterworth filter with a cut-off frequency of 100 Hz [7]. To compute maximal lower extremity joint moments the inverse dynamics method was employed. Calculations of maximal joint moments, which began when the foot segment made initial ground contact, were normalized and expressed as a percentage of body weight and height [50] (Fig. 2). Peak VGRFs were computed following time synchronization of kinetic and analog data, normalized and expressed as a percentage of body weight [50] (Fig. 3).

Neuromuscular assessments

Proper skin preparation was completed in order to improve fixation of electrodes and reduce electrical

Fig. 3 Participant performing a vertical drop landing at peak vertical ground reaction force

impedance [12, 43, 49]. Self-adhesive Ag/AgCl bipolar surface electrodes (Medicotest Inc., Rolling Meadows, IL, USA) 10 mm in diameter were positioned in pairs 25 mm apart over the mid-belly of appropriate musculature in line with the direction of myofibers [12, 43, 49]. Standard anatomic locations for placing electrodes were identified by palpation of respective mid-belly musculature during isometric contraction [12]. Accurate electrode fixation was established through standard isolated manual muscle testing procedures [12]. A single reference electrode was placed on the anteromedial aspect of the tibial tuberosity [13, 49].

Myoelectric signal activity collected by surface electrodes was conveyed to a battery-operated frequency modulated (FM) transmitter (Noraxon Inc., Scottsdale, AZ, USA) fixed to the subject and processed by the Noraxon Telemyo System (Noraxon Inc., Scottsdale, AZ, USA). The FM transmitter contains a single-ended amplifier (gain 500) filtered at a rate of Butterworth low-pass (15 Hz) and high-pass (500 Hz) with a common mode rejection ratio of 130 db. Surface EMG signals were converted from analog to digital data via a DT3010/32 (32 channel, 12bit) A/D board (Data Translation Inc., Marlboro, MA, USA) sampled at a frequency of 1,200 Hz. The signal was then transmitted to a computer system where raw SEMG data for all musculature were rectified and integrated by the Peak Motus software. The integrated SEMG values were calculated during the 128 ms prior to initial ground contact permitting collection of preparatory muscle activity and 250 ms following initial ground contact to allow recording of reactive muscle activity [13, 37, 49]. Integrated SEMG preparatory and reactive muscle activation of the following musculature was assessed: vastus medialis, vastus lateralis, medial hamstring, lateral hamstring and medial gastrocnemius. The measurement of separate maximal volitional isometric contractions (MVICs) was collected to normalize integrated SEMG data for respective musculature. Maximal volitional isometric contractions were sampled for 6 s to ensure maximum torque values were attained [43]. Furthermore, a SEMG signal was considered muscular contraction pending the neuromuscular activity exceeded a set trigger level of 10% MVIC [43]. Integrated SEMG values were averaged across three VDL trials for each participant. Goodwin et al. [24] established the validity and reliability of utilizing integrated SEMG of the lower extremity to assess neuromuscular activity with vertical jumping. Co-contraction of the quadriceps and hamstrings, which represents synchronized activation of agonist and antagonist muscles, was also calculated from the normalized integrated SEMG. Co-contraction muscle activity data sets, both preparatory and reactive, were computed by utilizing the equation employed by Rudolph et al. [44]. This method presents an approximation of the comparative quadriceps and hamstrings muscles activity as well as scale of the co-contraction during single-leg VDL [44].

Strength and endurance measurements

Isokinetic hamstrings muscular strength and endurance was tested with the Biodex System 3 Dynamometer (Biodex Medical Inc., Shirley, NY, USA) calibrated to specifications outlined by the manufacturer. Parameters assessed included bilateral concentric knee flexion peak torque (% BW) [N m], time to peak torque (ms) at 60° s^{-1} and endurance (total work) [*J*] at 240° s^{-1}. Torque values were automatically adjusted for gravity via Biodex Advantage Software (Biodex Medical Inc., Shirley, NY, USA). These velocities were chosen due to their dominance in applicable literature assessing muscular strength and endurance post ACLR [2, 4, 34, 56, 57]. Kannus et al. [29] established validity of peak moment in strength assessments and reliability of the parameter as a significantly reproducible variable to calculate via isokinetic dynamometry. Feiring et al. [21] established reliability and validity for isokinetic concentric modes of knee joint flexion peak moment at 60° s^{-1} and knee joint flexion work at 240° s^{-1}. Participants were seated and secured in an upright position upon the dynamometer via torso, pelvic and thigh straps. Participants folded arms across chest while seated to restrain excessive body displacement. The lateral femoral epicondyle was referenced in aligning the knee axis of rotation with the dynamometer resistance adaptor axis. At the onset of testing, participants were instructed to observe the system's computer monitor during data collection in an attempt to visualize attainment and maintenance of maximal force or velocity output. Testing at 60° s^{-1} consisted of three warm-up trials followed by three sub-maximal repetitions. Final measurement of strength was based upon three maximal repetitions of reciprocal knee joint flexion and extension [35]. Participants were given a 2-min rest interval before beginning endurance testing at $240°s^{-1}$ [35]. Prior to recording endurance data, participants were permitted five sub-maximal warm-up repetitions. Final measurement of endurance was based upon the participants completing as many maximal reciprocal knee joint flexion and extension concentric contractions as possible in a 45 s time period [35].

Data analyses

The sample size required to find statistical significance in this study was 14 participants per ISGA ACLR and control groups based on previous literature [19]. Variables for hamstrings muscular strength and endurance, preparatory and reactive muscle activation, hip and summated extensor moments as well as peak hip, knee and ankle joint flexion angles in addition to VGRF were evaluated. Separate dependent *t* tests were calculated to determine within group (involved/uninvolved) differences. Separate independent *t* tests were performed to analyze between group (ISGA ACLR/control) differences. A probability level of $P < 0.05$ was set a priori to denote statistical significance.

Results

Biomechanical analyses

Hip and net summated extensor moments did not significantly differ bilaterally within or between groups (Table 2). However, ISGA ACLR participants revealed significantly decreased peak VGRF landing upon the involved lower extremity compared to uninvolved ($P = 0.028$) and matched ($P < 0.0001$) controls (Table 2; Fig. 4).

Participants having undergone ISGA ACLR also displayed greater peak hip joint flexion angles landing upon the involved lower extremity compared to uninvolved ($P = 0.020$) and matched ($P = 0.026$) controls at initial ground contact (Table 2; Fig. 5). The ISGA ACLR group furthermore exhibited increased peak hip joint flexion angles landing upon the involved lower extremity compared to uninvolved ($P = 0.019$) and matched ($P = 0.007$) controls at peak VGRF (Table 2; Fig. 6). Moreover, ISGA ACLR participants demonstrated greater peak knee ($P = 0.005$) and ankle ($P = 0.017$) joint flexion angles when landing upon the involved lower extremity compared to the matched control at peak VGRF (Table 2; Figs. 7, 8).

Neuromuscular assessments

No significant differences were demonstrated in preparatory muscle activation of the quadriceps and hamstrings within or between groups. However, ISGA ACLR participants elicited significant increases in reactive muscle activation of the vastus medialis ($P = 0.013$), vastus lateralis ($P = 0.008$) and medial hamstrings ($P = 0.024$) landing upon the involved lower extremity compared to the matched control (Table 3; Fig. 10). Furthermore, the ISGA ACLR group produced significantly less medial gastrocnemius preparatory ($P = 0.005$) and reactive ($P = 0.010$) muscle activation landing upon the involved lower extremity compared to the uninvolved internal control (Table 3; Figs. 9, 10). In addition, ISGA ACLR participants exhibited significantly greater preparatory ($P = 0.033$) and reactive ($P = 0.022$) quadriceps and hamstrings co-contraction muscle activity landing upon the involved lower extremity compared to the matched control (Table 3; Figs. 11, 12).

Strength and endurance measurements

Measurements of isokinetic hamstrings muscular strength and endurance did not produce significant differences within or between groups (Table 4).

Discussion

The objectives of this research study were to investigate neuromuscular and biomechanical profiles of the lower extremity post ISGA ACLR compared to internal and matched controls with performance of single-leg 30 cm VDLs, a functional task and associated mechanism of ACL injury. An additional facet included measuring hamstrings muscular strength and endurance following harvest of the ISGA for ACLR. The significant results of this research study suggest that ISGA ACLR participants demonstrated unique kinetic, kinematic and muscle activation strategies with execution of VDLs upon the involved lower extremity compared to controls. Furthermore, these participants demonstrate no significant indication of hamstrings muscular strength and endurance deficiencies subsequent to ISGA ACLR.

Strength and endurance measurements

Contrary to previous investigations [4, 19, 26, 34, 56, 57] of isokinetic knee flexion strength and endurance, the results of this research study did not corroborate such

Table 2 Kinetic and kinematic analyses

	Involved	Uninvolved	*P* value
HipEM (N m/kg)	0.240 ± 0.060	0.270 ± 0.070	0.099
SEM (N m/kg)	0.590 ± 0.110	0.610 ± 0.090	0.286
VGRF (BW)	3.72 ± 0.510	4.19 ± 0.940	0.028*
	Involved	Matched	*P* value
HipEM (N m/kg)	0.240 ± 0.060	0.280 ± 0.090	0.119
SEM (N m/kg)	0.590 ± 0.110	0.62 ± 0.110	0.205
VGRF (BW)	3.72 ± 0.520	5.11 ± 1.07	0.0001*
	Involved at IGC	Uninvolved at IGC	*P* value
Hip (°)	29.7 ± 9.03	25.6 ± 8.30	0.020*
Knee (°)	24.6 ± 12.9	22.4 ± 6.23	0.285
Ankle (°)	15.2 ± 11.1	17.6 ± 4.50	0.235
	Involved at IGC	Matched at IGC	*P* value
Hip (°)	29.7 ± 9.03	23.6 ± 6.58	0.026*
Knee (°)	24.6 ± 12.9	18.8 ± 7.72	0.081
Ankle (°)	15.2 ± 11.1	18.7 ± 7.26	0.167
	Involved at peak VGRF	Uninvolved at peak VGRF	*P* value
Hip (°)	31.7 ± 8.88	27.7 ± 9.61	0.019*
Knee (°)	37.0 ± 9.75	33.0 ± 6.38	0.091
Ankle (°)	–3.25 ± 6.24	–0.38 ± 6.43	0.152
	Involved at peak VGRF	Matched at peak VGRF	*P* value
Hip (°)	31.7 ± 8.88	24.2 ± 6.02	0.007*
Knee (°)	37.0 ± 9.75	27.8 ± 7.52	0.005*
Ankle (°)	–3.25 ± 6.24	1.87 ± 5.87	0.017*

Hip extensor moment (HipEM), net summated extensor moment (SEM) and vertical ground reaction force (VGRF). Peak hip, knee and ankle joint flexion angles at initial ground contact (IGC) and peak vertical ground reaction force (VGRF)

* $P < 0.05$ denotes statistical significance

Values are mean ± SD

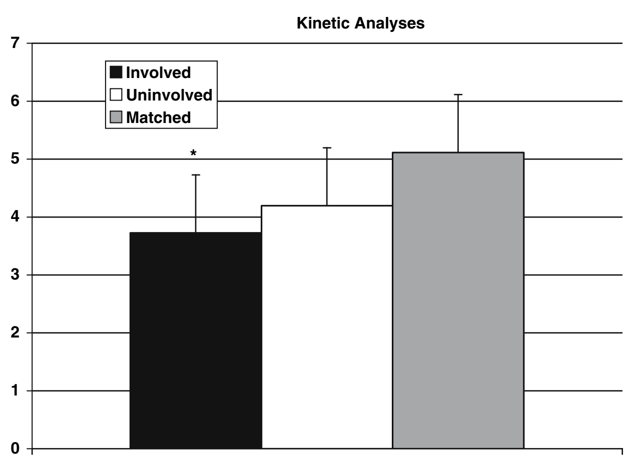

Fig. 4 *$P < 0.05$ denotes significantly decreased peak vertical ground reaction force landing upon the involved lower extremity compared to controls

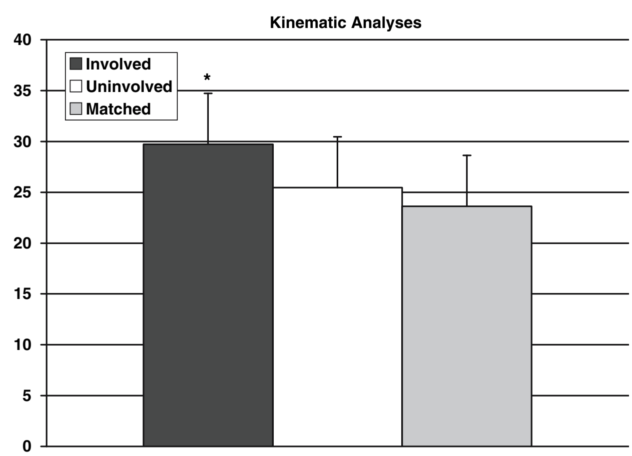

Fig. 5 *$P < 0.05$ denotes significantly greater peak hip joint flexion angles landing upon the involved lower extremity compared to controls at initial ground contact

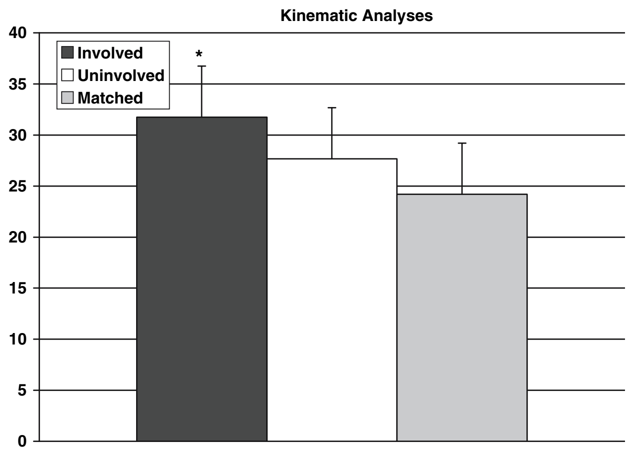

Fig. 6 *$P < 0.05$ denotes significantly greater peak hip joint flexion angles landing upon the involved lower extremity compared to controls at peak vertical ground reaction force

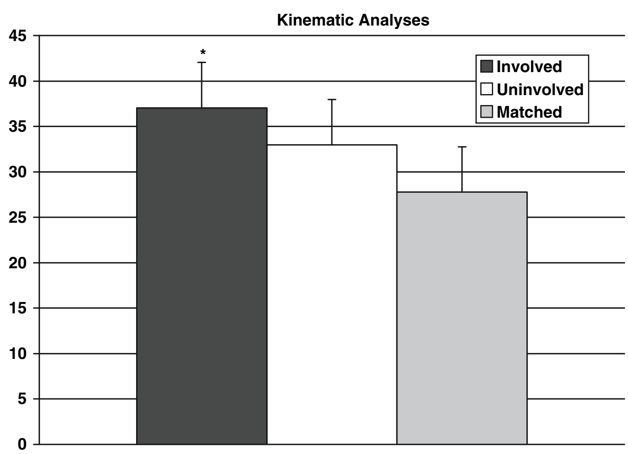

Fig. 7 *$P < 0.05$ denotes significantly greater peak knee joint flexion angle landing upon the involved lower extremity compared to the matched control at peak vertical ground reaction force

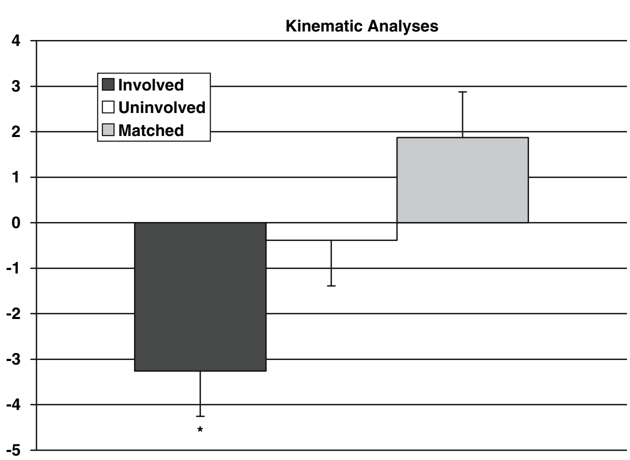

Fig. 8 *$P < 0.05$ denotes significantly greater peak ankle joint flexion angle landing upon the involved lower extremity compared to the matched control at peak vertical ground reaction force

significant hamstrings muscular weakness post ISGA ACLR. This lead to the rejection of our initial hypothesis, which stated donor site morbidity consequent to harvest of the ISGA for ACLR would yield hamstrings strength and endurance deficits, suggesting insufficiency in restricting ATSFs. Instead our findings were comparable to those of Aglietti et al. [2], in that harvesting of the ISGA caused no detrimental effects on hamstrings performance as measured by isokinetic dynamometry. Similar observations to these results regarding isokinetic quadriceps muscular performance post IBPTBA ACLR have been previously documented [47, 48]. It should be noted that as prevalent in prior applicable experiments [4, 26, 34, 57], all ISGA ACLR participants enrolled in this research study completed similar sports rehabilitation protocols emphasizing strength and conditioning of hamstrings musculature. Therefore, our results emphasize the importance of hamstrings strength and conditioning training, which may supplement the musculature's passive tone as well as co-contraction force [5]. Augmenting hamstrings muscular performance may enhance its synergistic role to the ACL and intra-articular graft [16, 27]. This may aid in efficiently moderating ATSFs and knee joint rotary instability during functional tasks such as landing [27, 37].

Biomechanical analyses

The second hypothesis of this research study stated that as a result of donor site morbidity yielding hamstrings muscular weakness, the capacity of involved lower extremities to generate a hip or maintain net summated extensor moments would be significantly diminished. In contrast, the results observed in this research study did not confirm this hypothesis. Our findings also fail to complement the observations in a similar experiment specific for IBPTBA ACLR conducted by Ernst et al. [19]. Ernst et al [19] reported decreased knee and net summated extensor moments with the performance of vertical jump landings post IBPTBA ACLR. This suggested an insufficient attenuation of impact [19] and susceptibility to limb collapse [54] as the result of potential quadriceps muscular weakness [19]. However, the absence of diminished extensor moments subsequent to donor site morbidity may not have emerged post ISGA ACLR as a result of specific graft harvest location. Therefore, graft harvest of the distal insertion of medial hamstrings musculature may not be severely detrimental to correct biomechanical function of the proximal hip joint in maintaining lower extremity stability with execution of VDLs. In this role, contribution of the semitendinosus and gracilis to generate a hip extensor moment may not be as vital as gluteal musculature. Furthermore, the fact that hamstrings musculature is

Table 3 Neuromuscular assessments

Preparatory	Involved	Uninvolved	*P* value
Vastus medialis (%MVIC ms)	0.104 ± 0.063	0.099 ± 0.056	0.169
Vastus lateralis (%MVIC ms)	0.084 ± 0.041	0.095 ± 0.060	0.232
Medial hamstrings (%MVIC ms)	0.077 ± 0.063	0.120 ± 0.253	0.300
Lateral hamstrings (%MVIC ms)	0.074 ± 0.048	0.107 ± 0.131	0.250
Medial gastrocnemius (%MVIC ms)	0.150 ± 0.043	0.225 ± 0.104	0.005*
Preparatory	Involved	Matched	*P* value
Vastus medialis (%MVIC ms)	0.104 ± 0.063	0.090 ± 0.037	0.245
Vastus lateralis (%MVIC ms)	0.084 ± 0.041	0.083 ± 0.039	0.472
Medial hamstrings (%MVIC ms)	0.077 ± 0.063	0.046 ± 0.029	0.058
Lateral hamstrings (%MVIC ms)	0.074 ± 0.048	0.052 ± 0.024	0.071
Medial gastrocnemius (%MVIC ms)	0.150 ± 0.043	0.151 ± 0.023	0.489
Reactive	Involved	Uninvolved	*P* value
Vastus medialis (%MVIC ms)	0.424 ± 0.300	0.428 ± 0.315	0.230
Vastus lateralis (% MVIC ms)	0.339 ± 0.170	0.359 ± 0.372	0.390
Medial hamstrings (%MVIC ms)	0.177 ± 0.182	0.147 ± 0.273	0.364
Lateral hamstrings (%MVIC ms)	0.201 ± 0.292	0.345 ± 0.470	0.231
Medial gastrocnemius (%MVIC ms)	0.123 ± 0.069	0.225 ± 0.164	0.010*
Reactive	Involved	Matched	*P* value
Vastus medialis (%MVIC ms)	0.424 ± 0.300	0.231 ± 0.065	0.013*
Vastus lateralis (%MVIC ms)	0.339 ± 0.170	0.211 ± 0.075	0.008*
Medial hamstrings (%MVIC ms)	0.177 ± 0.182	0.074 ± 0.039	0.024*
Lateral hamstrings (%MVIC ms)	0.201 ± 0.292	0.106 ± 0.085	0.127
Medial gastrocnemius (%MVIC ms)	0.123 ± 0.069	0.104 ± 0.040	0.183
Preparatory co-contraction	Involved	Uninvolved	*P* value
Q & H (%MVIC ms)	0.253 ± 0.162	0.195 ± 0.106	0.174
	Involved	Matched	*P* value
Q & H (%MVIC ms)	0.253 ± 0.162	0.159 ± 0.086	0.033*
Reactive co-contraction	Involved	Uninvolved	*P* value
Q & H (%MVIC ms)	0.465 ± 0.397	0.623 ± 0.781	0.255
	Involved	Matched	*P* value
Q & H (%MVIC ms)	0.465 ± 0.397	0.225 ± 0.146	0.022*

Preparatory and reactive muscle activation of the lower extremities. Preparatory and reactive co-contraction muscle activity of the quadriceps (*Q*) and hamstrings (*H*)

* $P < 0.05$ denotes statistical significance

Values are mean ± SD

secondary and not prime movers of hip extension may be noteworthy.

Although kinematic data were not direct variables of interest for purposes of addressing hypotheses in this research study, it is of assistance for interpreting the kinetic results observed. This is especially true for identifying additional factors contributing to decreased peak VGRF elicited by ISGA ACLR participants landing upon the involved lower extremity compared to controls. A viable explanation may be dependent upon landing strategies incorporated by the ISGA ACLR group. Numerous research studies have investigated lower extremity

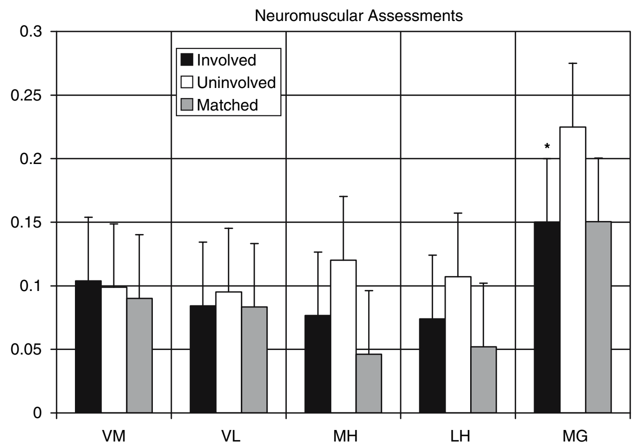

Fig. 9 Preparatory muscle activation of the vastus medialis (VM), vastus lateralis (VL), medial hamstrings (MH), lateral hamstrings (LH) and medial gastrocnemius (MG). *$P < 0.05$, denotes significantly less preparatory muscle activation of the medial gastrocnemius landing upon the involved lower extremity compared to the uninvolved control

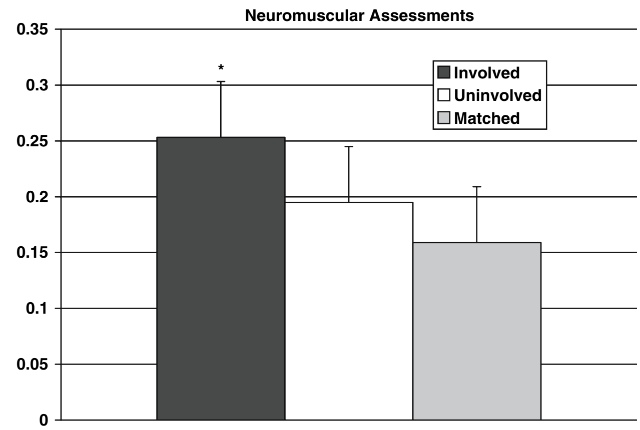

Fig. 11 Preparatory co-contraction muscle activity of the quadriceps and hamstrings. *$P < 0.05$, denotes significantly greater preparatory co-contraction muscle activity landing upon the involved lower extremity compared to the matched control

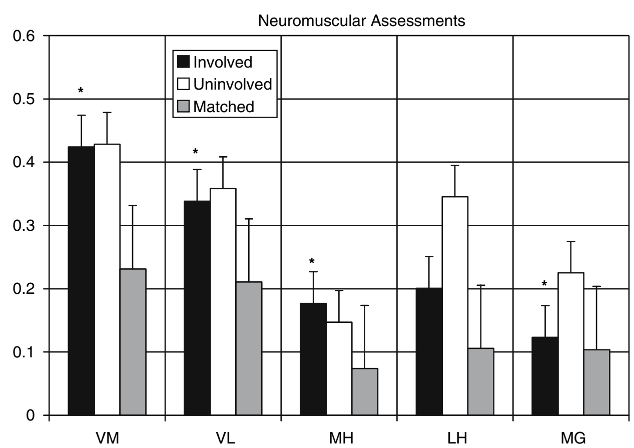

Fig. 10 Reactive muscle activation of the vastus medialis (VM), vastus lateralis (VL), medial hamstrings (MH), lateral hamstrings (LH) and medial gastrocnemius (MG). *$P < 0.05$, denotes significantly greater reactive muscle activation of the vastus medialis, vastus lateralis and medial hamstrings landing upon the involved lower extremity compared to the matched control 250 ms post initial ground contact. *$P < 0.05$, also denotes significantly less reactive muscle activation of the medial gastrocnemius landing upon the involved lower extremity compared to the uninvolved control

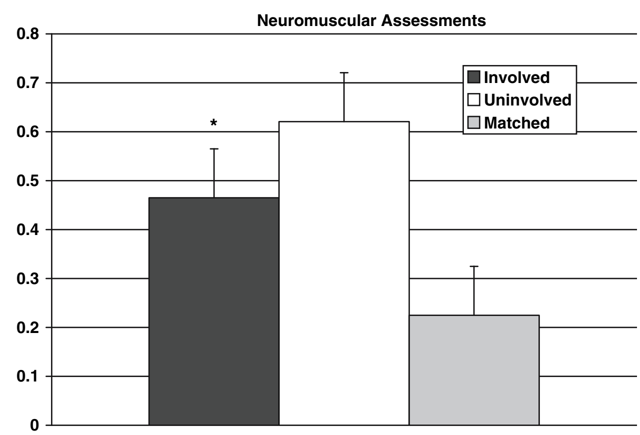

Fig. 12 Reactive co-contraction muscle activity of the quadriceps and hamstrings. *$P < 0.05$, denotes significantly greater reactive co-contraction muscle activity landing upon the involved lower extremity compared to the matched control

kinematics during execution of hard and soft landings [6, 11, 14]. In general, soft landings yielding decreased peak VGRF are associated with greater peak knee joint flexion angles [6, 11, 14]. Devita et al. [14] further characterized soft landings by a pattern of inclusive increased peak lower extremity joint flexion angles. This consisted of peak hip and knee joint flexion angles being approximately 9° greater and the peak ankle joint flexion angle approximately 5° greater compared to hard landings [14]. Consistent with soft landings, ISGA ACLR participants in this research study demonstrated greater peak hip joint flexion angles at initial ground contact upon the lower extremity compared to controls. The ISGA ACLR group also produced greater peak hip, knee and ankle joint flexion angles at peak VGRF landing upon the involved lower extremity compared to controls. Although in this research study the effect of biomechanical landing techniques on ACL and graft loads are unknown, we suggest ISGA ACLR participants exhibit unique kinematic profiles of the involved lower extremity joints. We propose the increased peak involved lower extremity joint flexion angles may indicate the ISGA ACLR group altered their landing strategies in a manner that diminished impact loads to the knee [6, 11, 14, 17, 18]. This may be an attempt to reduce the risks of further injury to the previously reconstructed knee joint.

Table 4 Strength and endurance measurements

	Involved	Uninvolved	*P* value
Peak torque/BW (%)	51.7 ± 33.7	51.5 ± 32.2	0.469
Time to peak torque (ms)	460.7 ± 249.5	557.9 ± 260.8	0.107
Total work (J)	1,030.6 ± 476.2	1,023.9 ± 294.2	0.466
	Involved	Matched	*P* value
Peak torque/BW (%)	51.7 ± 33.7	43.6 ± 12.9	0.203
Time to peak torque (ms)	460.7 ± 249.5	542.9 ± 326.5	0.231
Total work (J)	1,030.6 ± 476.2	852.4 ± 288.2	0.121

Isokinetic hamstrings muscular strength and endurance measurements of peak torque at 60° s^{-1}, time to peak torque at 60° s^{-1} and total work at 240° s^{-1}

Values are mean ± SD

Neuromuscular assessments

Based on the findings of Wojtys et al. [56], which documented ensuing quadriceps neuromuscular deficits subsequent to knee joint perturbation in IBPTBA ACLR participants, we hypothesized similar insufficiencies in hamstrings reactive muscle activity would arise in the ISGA ACLR group with VDLs. From the observations of McNair et al. [37] we drew our final hypothesis stating that as the result of significant hamstrings neuromuscular deficiencies, ISGA ACLR participants would exhibit amplified VGRFs landing upon the involved lower extremity. However, the results of this research study caused us to reject both hypotheses. Instead the ISGA ACLR group recorded significant increases in hamstrings reactive muscle activity concomitant with decreased peak VGRF landing upon the involved lower extremity compared to controls. Our findings prove coherent with the work of McNair et al. [37], which noted participants demonstrating heightened muscle activation of the hamstrings typically produced significantly lower peak VGRF upon landings [37]. These observations emphasize the importance of hamstrings muscle activation in dampening peak VGRFs and potentially restraining ATSFs during landing [37]. Hence, the protective role of hamstrings musculature in the dynamic restraint mechanism of the knee joint should not be underestimated. Such deficiencies in hamstrings muscle activation during functional tasks may escalate susceptibility for ACL or associated knee joint trauma subsequent to heightened peak VGRFs and excessive ATSFs.

Additional results of our neuromuscular assessments also noted ISGA ACLR participants produced greater quadriceps and hamstrings preparatory and reactive co-contraction muscle activity landing upon the involved lower extremity compared to the matched control. Prior observations for the capability of quadriceps and hamstrings co-activation mechanisms to decrease ATSFs [16, 27, 40] as well as rotary tibial displacement [27] have been documented. However, this mechanism could be possibly hindered if hamstrings muscular performance is not operating at optimum capacity [27]. Our co-contraction findings may suggest unique strategies in preserving knee joint stability with VDLs as well as complement previous research studies [16, 27, 40] investigating similar variables. Hence, our results possibly indicate the potential capacity of quadriceps and hamstrings musculature to act collectively in protecting the intra-articular ISGA from excessive and extreme loads during landing. Moreover, our observations reinforce the clinical application of therapeutic exercise for hamstrings musculature with individuals who have undergone ISGA ALCR to preserve this potential advantageous mechanism.

Accompanying findings in this research study demonstrate significantly diminished muscle activation of the gastrocnemius for the ISGA ALCR group landing upon the involved lower extremity compared to the uninvolved internal control. Comparatively, Limbird et al. [32] revealed ACLD participants produce significantly less gastrocnemius muscle activation during gait. Previous experiments [22, 27, 40] have suggested the gastrocnemius musculature to antagonize the ACL. Consequently, knee joint flexor moments are generally considered to shield the ACL and intra-articular graft from excessive loads. Although gastrocnemius musculature is capable of generating a knee joint flexor moment, its antagonistic relationship to the ACL suggests fundamental clinical implications [22, 40]. Therefore it is vital to assess the ratio of knee joint flexion and force generated by gastrocnemius musculature when considering modes of sports rehabilitation. This may assist in assessing the potential ability to shield or load the intra-articular graft post ACLR.

The findings in this retrospective research study should be interpreted with accounting for certain inherent limitations. An obvious limitation includes the confines of a controlled laboratory setting where participants were sensitive to experimental procedures. Though this permits favorable comparison for the variables of interest within and between groups, it fails to accurately represent a true simulation of "live" athletic environments. Confounding variables may exist in a "live" event that potentially renders landings erratic and perilous from those performed in a controlled laboratory setting. Moreover, the protocol landing method utilized, which consisted of procedural constraints is not common to landings observed in "live" athletic events. Though this augments internal validity for a research study, it unfortunately diminishes the general application of our results to sports. Furthermore, although no significant differences where discovered throughout the recreationally active participant demographics, this does not verify equivalent aptitude for VDLs among sampled populations. Various participants may have demonstrated superior proficiency than others with the execution of VDLs. Greater homogeneity among participants such as limiting the sample populations to recreational basketball or gymnastic athletes may increase internal validity of the research study yet decrease the general application of our findings. Neuromuscular and biomechanical performance exhibited by ISGA ACLR participants requires conclusive determination by prospective long-term research studies. This will aid in accounting for maintenance or detriment of such strategies and techniques found in this research study. Furthermore, two different orthopedic surgeons performed the ISGA ACLR procedures. As such, the potential of inter-surgeon variability yields an issue. Moreover, the results of this research study are only applicable to recreational athletes. This necessitates the investigation of additional sample populations to compare our findings. Future objectives should incorporate advanced neuromusculoskeletal models and research methods to scrutinize the results of this study. Additional research in this area of interest may bring about auxiliary comprehension of neuromuscular control and biomechanics in knee joint stability as well as establish supporting data to ascertain finite landing techniques that are deemed representative of ACLD, ACLR and control populations for most valid comparisons within and between groups. Further investigation of these variables will also serve the imminent advancement of surgical interventions as well as sports rehabilitation techniques specific to ISGA ACLR.

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