Effect of Anterior Cruciate Ligament Reconstruction on the Passé Movement in Elite Dancers

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Abstract

Semitendinosus-gracilis (STG) and patella-tendon-bone (PTB) are frequently selected grafts for anterior cruciate ligament (ACL) reconstruction in dancers. While STG and PTB grafts appear to be similar in restoring acceptable mechanical joint stability, it is not known whether there are alterations in the kinematics of dance movements following these procedures. The present study examined two-dimensional kinematics of trunk-lower extremity coordination in 18 adult professional dancers: six dancers with STG, six with PTB graft ACL reconstruction, and six healthy controls. All dancers with ACL reconstruction had returned to full dancing and performance with no visible asymmetries in their dancing. We examined whether temporal organization and peak velocity of the gesture limb differed between dancers with STG and PTB graft reconstruction and controls when performing the passé. Hip and knee peak angular velocities were slower on the involved limb of STG and PTB dancers compared to controls. Adaptations were seen bilaterally in delayed movement times, shorter deceleration times, and greater number of movement units in the ACL reconstruction groups. These findings suggest that injury to a single joint can affect kinematics throughout the involved and uninvolved lower extremities. The altered movement patterns found in dancers with both types of ACL reconstruction suggest that their control of complex movements may be adaptive in nature.

Both semitendinosus-gracilis (STG) and patella-tendon-bone (PTB) are frequently selected grafts for anterior cruciate ligament (ACL) reconstruction in dancers. Selection of STG as a surgical graft for dancers has been justified by the relatively high incidence of patella-femoral problems in dancers, the requirement of genu recurvatum for the aesthetic line of select dance movements (dèveloppé), and the tendency for dancers to have generalized ligamentous laxity.[1] Studies have shown acceptable results in the general population for both types of reconstruction in strength, laxity, and performance as quantified by self-rated outcome questionnaires and functional tests (e.g., triple hop, shuttle run, vertical hop).[2-6] Undesirable outcomes following PTB reconstruction include quadriceps weakness, patella-femoral irritation, and flexion contracture.[2,7-9] Problems following STG reconstruction include hamstrings weakness, increased laxity, and lower self-rated outcome scores.[2,7,8] Both STG and PTB ACL reconstruction outcomes appear to be similar, restoring acceptable mechanical joint stability. However, few studies have assessed both STG and PTB ACL reconstruction using kinematic analysis of whole body movements. It is not known whether there are alterations in the kinematics of dance movements following these procedures, compared to healthy controls.

It has been suggested that reconstruction of the ACL in young, active individuals is advised when adaptations are unsuccessful in eliminating joint instability.[10,11] However, while mechanical joint stability is restored and angular kinematics of gait following PTB ACL reconstruction are similar to healthy controls, significant kinetic adaptations persist in gait, stair climbing, and more demanding activities such as jogging and pivoting

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or cutting following PTB ACL reconstruction.[12-16] Furthermore, ACL reconstruction appears to have little impact on balance and postural control, as ACL reconstruction subjects continue to differ from controls on both their reconstructed as well as their uninvolved limb in perturbation studies of single limb stance.[17,18] Therefore, it is also important to assess the movement and postural control of both types of ACL reconstruction (PTB and STG) in both the involved and uninvolved limbs.

Although mechanical joint stability can be successfully restored with ACL reconstruction, sensory input may remain altered. STG and PTB ACL reconstruction groups show deficits in threshold to detection of passive motion of their reconstructed limb compared to their uninvolved limb, as well deficits bilaterally compared to controls.[19,20] Muscle recruitment order remains altered following PTB ACL reconstruction; and this deficit is also bilateral.[21] Response to single-legged postural perturbation remains longer in PTB ACL reconstruction subjects on both involved and uninvolved limbs, compared to controls.[17,18] The loss of afferent information due to ACL injury may result in modifications of the central nervous system in patients with ACL deficiency, resulting in altered neuromuscular function bilaterally. This change may persist despite ACL reconstruction.[22]

The focus of biomechanical analysis following ACL reconstruction has been on the weightbearing limb in activities such as pivoting, running, and stair-climbing. However, the focal point of dance expression is the non-weightbearing lower extremity or gesture limb. One of the requirements to dance at the elite level is the facility to efficiently perform lower extremity movements at multiple heights, shapes, and velocities. The effect of musculoskeletal injury to the dancer is, perhaps, more devastating than to other professional athletes because the goal of dance is the movement itself. The effect of ACL reconstruction on gesture limb movements of dancers has not been analyzed.

Dancers are an ideal population in which to study kinematics because dance training incorporates highly specific movements that require precise spatial and temporal coordination. Dancers must attain mastery of highly stylized movements under various balance, postural, and support conditions with minimal variability. The dance movement selected for analysis in this study (passé) was shown previously to be performed at a high level of spatial and temporal consistency by healthy professional male and female dancers.[23] In the passé, the hip and knee are constrained to move together. Postural adjustments, which precede limb movement, must be made to maintain stability. The temporal and spatial movement demands necessary to perform the passé correctly thus leave little potential for variation. Nevertheless, the temporal coupling between the trunk and limb and velocity characteristics of the gesture limb are free to vary.

The purpose of this study was to determine whether the temporal organization and velocity of the gesture limb differs in STG and PTB ACL reconstruction dancers (involved and uninvolved limbs) compared to healthy dancers (controls) when performing the passé. Each dancer was able to achieve the shape and timing of the movement at a level that allowed their return to professional dance. We predicted that the postural adjustments associated with the onset of trunk movement and the initiation and completion of toe movement would be less tightly coupled following ACL reconstruction. We hypothesized that gesture limb velocity would be slower and less continuous for both groups of ACL reconstruction dancers. Lower peak velocity might also affect the acceleration to deceleration ratios in order to maintain overall movement timing.

Methods

Subjects

Eighteen male and female professional dancers between the ages of 20 and 43 participated including: six healthy dancers (control group), six dancers with unilateral STG reconstruction (STG group), and six dancers with unilateral PTB reconstruction (PTB group). There were five females and one male in each group. Appropriate sample size was determined by a power analysis using pilot knee angular velocity data. With three independent samples, an alpha level of 0.05, and, by convention, a power of 0.80 and an effect size index of 0.80, a sample size of six was required.[24] Gender and limb preference were not controlled as our previous work indicated no differences in these variables in the passé at the elite level.[23]

Subjects with ACL reconstruction met the following inclusion criteria: 1. unilateral autogenous ACL reconstruction at least 9 months prior to study, 2. completion of rehabilitation, 3. return to a full dancing schedule (including performances), and 4. no history of further knee injury after ACL reconstruction. Exclusion criteria for control subjects included: 1. history of lower extremity injury during the previous six months resulting in missed performances, rehearsals, or classes; or 2. any history of knee ligament injury. Informed consent was obtained from each subject, as approved by the Institutional Review Board at Teachers College, Columbia University.

Subjects were recruited from the professional dance community and dance medicine specialists. The mechanism of ACL injury for each of the dancers was noncontact in nature and involved either taking off or landing on one leg from a jump or descent from a partnered lift. The STG and PTB surgery was performed by several different orthopaedic surgeons who frequently perform ACL reconstruction using standard ipsilateral harvesting techniques (for PTB, central third of the patella tendon; and for STG, double loop) and fixation (for PTB, interference screw; and for STG, screw-washer). Rehabilitation protocols were conducted by physical therapists who regularly work with the referring orthopaedists and specialize in dance medicine.

Subjects were screened with dance training, injury, and knee activity (modified Cincinnati Knee Rating System,[25] a shortened adaptation of the Cincinnati Knee Rating System) questionnaires, and were measured for passive knee and hip range of motion (ROM) with a standard goniometer. Preferred first position turnout (heels touching with hips externally rotated) was quantified by measuring the angle formed by a line drawn from each second toe to a center point between the heels.[26] Subjects also underwent knee isokinetic testing at 90°/sec and 180°/sec (Biodex, Single Chair System 2, Biodex Medical Systems, Inc., Shirley, NY) and knee arthrometry to test ACL laxity (KT-2000, Medmetrics, San Diego, CA).

Control and ACL reconstruction group descriptive variables were compared using separate ANOVAs. All subjects performed in national level companies, had a range of 14 to 30 years of dance training, and danced professionally for 4 to 22 years. There were no differences between control and ACL reconstruction groups in age, height, weight, number of years dancing, years as a professional, knee ROM, or first position turnout (Table 1).

ACL reconstruction subjects displayed mean isokinetic deficits of 17% (± 14%) quadriceps and 7% (± 6%) hamstrings peak torque at 90°/sec, compared to their uninvolved side. There were no differences for control subjects between preferred and non-preferred limbs in isokinetic peak torque values. Isokinetic peak torque values for the STG and PTB groups were comparable. However, significant differences were found between control and the ACL-reconstruction groups in quadriceps peak torque at 90°/sec ($p < 0.05$) and 180°/sec ($p < 0.01$) (Table 1). There were also no differences between STG and PTB groups in mean knee activity score, post-operative time, or ACL laxity values. STG and PTB reconstructed subjects ranged from 11 to 45 months post surgery. Knee activity scores were lower in the ACL-reconstruction groups compared to controls ($p < 0.01$). In summary, the two ACL-reconstruction groups were similar in standard parameters of ACL outcome, but were different from the control group.

Instruments

Two-dimensional kinematic analysis was conducted using the Peak Performance System (version 5.3, Peak Performance Technologies, Englewood, CO). A 60 Hz video camera and lighting were placed perpendicular to the frontal plane. Calibration was conducted according to the manufacturer's guidelines prior to each data collection session. Twelve reflective, spherical markers, 2.5 cm in diameter, were placed bilaterally at the anterior acromion, anterior superior iliac spine (ASIS), anterior hip (hip), medial knee joint line (knee), medial malleolus (ankle), and medial first metatarsal-phalangeal joint (toe) (Fig. 1). The hip marker was placed according to the method first reported by Andriacchi and confirmed by Kirkwood and colleagues, which has been found to be the most accurate non-invasive placement for kinematic and kinetic gait research.[27] Attire for all subjects consisted of a dark colored unitard and dark socks to maximize the contrast of reflective markers.

We addressed "out of plane" two-dimensional movement concerns by comparing the data in this study to data collected in three dimensions on several of the same subjects. Hip and knee flexion angular displacement values calculated with the Peak 2-D system were compared to passé data collected on the same healthy professional dancers in three dimensions using a 5-camera motion analysis system (Vicon 250, Oxford Metrics Ltd,

Table 1 Demographics

Group	Control	STG	PTB
Age (years)	30.7 ± 6.4	31.0 ± 9.5	28.7 ± 4.8
Gender	5 female, 1 male	5 female, 1 male	5 female, 1 male
Height (m)	1.62 ± 0.04	1.62 ± 0.05	1.66 ± 0.07
Weight (kg)	54.05 ± 11.89	53.07 ± 4.41	56.02 ± 10.81
Leg length (m)	1.08 ± 0.08	1.10 ± 0.06	1.11 ± 0.06
Total years dance	21.8 ± 6.5	19.8 ± 2.7	21.0 ± 5.6
Total years prof	14.3 ± 9.1	10.5 ± 7.4	8.6 ± 6.1
1st position (deg)	112.2 ± 5.4	111.5 ± 14.0	101.5 ± 10.6
Knee ROM (deg)	5.8 - 0 - 140	3.5 - 0 - 140	5.2 - 0 - 140
Knee activity score	97.7 ± 4.1	83.3 ± 3.1*	86.8 ± 4.9*
Post op time (mos)		29.3 ± 9.9	21.3 ± 12.2
Quadriceps peak torque deficit: 90°/sec	0.15 ± 2.25	16.77 ± 11.04*	16.64 ± 17.89*
Hamstrings peak torque deficit: 90°/sec	1.77 ± 0.94	6.67 ± 9.17	6.52 ± 4.41
Quadriceps peak torque deficit: 180°/sec	2.48 ± 1.03	15.95 ± 7.74*	7.62 ± 3.64*
Hamstrings peak torque deficit: 180°/sec	2.93 ± 0.87	10.13 ± 8.87	1.16 ± 4.77

*ANOVA: Knee activity score $p < 0.01$, post hoc Control v PTB and STG $p < 0.01$. Quadriceps peak torque deficit 90°/sec $p < 0.05$, post hoc Control v PTB and STG $p < 0.05$. Quadriceps peak torque deficit 180°/sec $p < 0.01$, post hoc Control v PTB and STG $p < 0.05$.

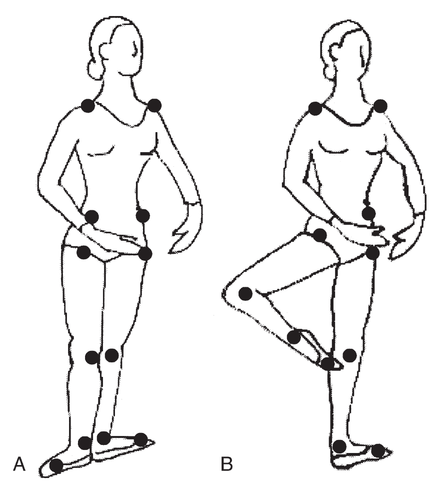

Figure 1 Passé movement; **A**, First position (initial and final posture); **B**, Passé position.

Oxford, UK). The angular displacement values were similar.

Data were automatically digitized using the Peak Performance 5.3 system, filtered with a dual pass, Butterworth filter with a low pass cutoff of 6 Hz, and scored with a custom program written in LabView (LabView, National Instruments Corp., Austin, TX).

Experimental Protocol

The temporal and spatial constraints of the movement were specified. Each dancer's preferred first position foot placement was marked on the floor as the starting position. Arm posture was designated as first position port de bras (arms form an oval shape in front of the dancer at mid-sternal height), which is traditionally used with the passé.[28] A marker was placed 1.5 m from the floor, on the wall behind the camera, to standardize the subjects' visual focus. A tape recording of a metronome with voice instruction overlay provided the tempo of the movement sequence. Subjects practiced the passé movements for one set of six consecutive repetitions with each limb to synchronize their movements with the metronome. One passé repetition consisted of moving from first position to passé and returning to first position again. The foot was drawn up the side of the stance limb until the great toe touched the medial joint line of the stance knee. The passé incorporates approximately 80° hip and 120° knee flexion (Fig. 1). Subjects were instructed to reach the height of the passé on the metronome count of "one," and to return the foot to the floor on the count of "two." Endpoint (toe) spatial accuracy was confirmed by an experimenter with expertise in dance.

Each subject performed a set of six consecutive passé movements with the right limb, rested one minute, and then performed a set of six consecutive passé sequences with the left limb. This was repeated for a second series with the right and left limbs, to complete the testing session (a grand total of 12 repetitions on each limb). Each set of six passé sequences was approximately eight seconds in length, with one passé sequence lasting approximately 1.2 seconds. The protocol designated six consecutive passé sequences because successive passé movements are often performed en pointe or as turns.

Data analysis

Each passé movement was scored as a separate trial. Interclass correlation coefficients (ICC) were conducted on each parameter to determine the reliability between the two sets of six trials per limb of each subject. The ICC values showed high reliability (range: 0.79 to 0.97). Since t-tests indicated no differences between trial sets, data from the two sets of six repetitions were pooled, making a total of 12 passé repetitions analyzed for each limb. The means of 12 trials for each limb of each subject in each parameter were used for subsequent analysis.

To test the hypothesis that trunk and limb movement temporal parameters are less tightly coupled following ACL reconstruction, onset and completion time of trunk and limb displacement on the gesture side were measured. Mean onset and termination times of trunk (represented by the ASIS marker) resultant displacement and limb (knee angular and toe resultant) displacement were calculated to ascertain temporal organization. Because the hip and knee move together, the knee marker was selected to represent them. To determine whether gesture limb velocities are slower in ACL-reconstruction groups we calculated the mean peak angular velocity of the hip and knee, and peak tangential velocity of the end-segment (toe) during the ascending and descending phases of the passé. The number of movement units in the velocity profiles of the hip, knee, and toe (velocity curves with multiple peaks) were determined to quantify movement continuity or smoothness. A movement unit corresponds to a local peak and valley (one acceleration and one deceleration) in the velocity profile.[29-31] To be considered a movement unit, a velocity peak had to exceed 10°/sec (hip or knee angular velocity) or 0.10m/sec (toe tangential velocity). Finally, to ascertain whether there are changes in relative timing (acceleration to deceleration ratio), percent time in deceleration was calculated for the hip, knee, and toe as a percentage of the ascent or descent velocity phase (time from peak velocity to movement completion divided by total phase time). In addition, the coefficient of variation (SD/mean x 100) was determined, as a measure of movement consistency, for each of the dependent variables.

Movement onset and termination was defined as three consecutive increases or decreases in displacement, respectively. Alternative thresholds (5% of mean displacement and two standard deviations from mean baseline) produced qualitatively similar results.

Separate between group ANOVAs were performed on each dependent variable obtained from movement of each limb. The independent variables were group and limb. For each dependent kinematic variable, control group non-preferred limbs were compared to STG and PTB group involved limbs, and control preferred limbs to STG and PTB uninvolved limbs. Previous work found no differences between preferred and non-preferred limbs in the passé kinematics of healthy elite dancers.[23] We could not control for whether the limb with ACL-reconstruction was preferred or non-preferred, therefore, we arbitrarily matched the non-preferred limbs of controls with the involved limbs of ACL reconstruction subjects. Post-hoc Bonferroni comparisons were conducted where appropriate. A nonparametric Kruskal-Wallis test for three independent groups was conducted for the movement unit variable. Differences were considered statistically significant at the $p < 0.05$ level.

Results

There were two distinct phases in the passé sequence: an ascent phase, from first position to passé, and a descent phase, from passé back to first position. Figure 2 displays a representative control dancer during one trial. A stick figure illustrating segmental position change of the right stance and left gesture sides is shown in Figure 2A. Movement began with translational motion at the trunk as weight shifted from the two-footed first position to single limb

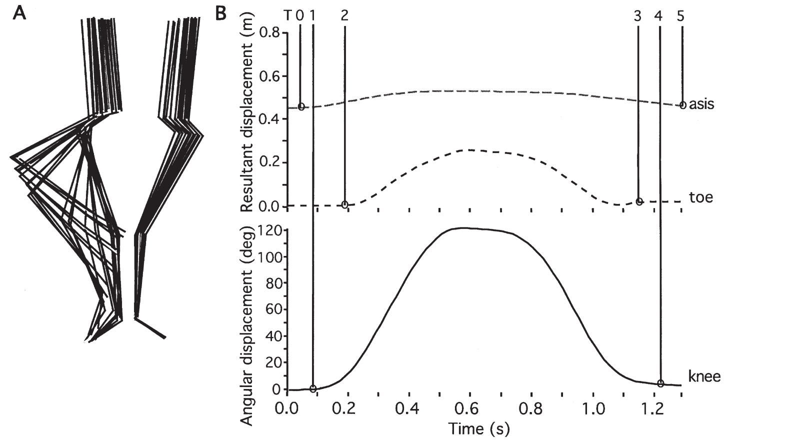

Figure 2 Stick figure and passé movement profile of a representative trial of one control subject. **A**, The stick figure illustrates segmental position change of the right stance and left gesture sides. **B**, Top: Resultant displacement curves of the gesture side ASIS and toe markers; Bottom: Angular displacement curve of the gesture knee, for the same trial of this subject. All traces are aligned to the temporal (x) axis. Movement initiation and termination of the gesture side markers are indicated by the vertical lines labeled T0-5. Trunk translation (T0 = ASIS) preceded gesture limb marker onset. Gesture limb movement followed a proximal to distal order at movement onset (T1 = knee, T2 = toe), and a distal to proximal order at movement termination (T3 = toe, T4 = knee). Trunk translation (T5 = ASIS) followed gesture limb marker termination to complete the sequence (returning to first position). ASIS = anterior superior iliac spine.

stance. The gesture hip and knee flexed, and the ankle plantar flexed as the foot pointed.

Figure 2B displays the traces of trunk and toe resultant displacement and gesture knee angular displacement, illustrating coordination of body segments. Movement initiation and termination of the gesture side markers are indicated by the vertical lines labeled T0 to T5. Trunk translation (T0 = ASIS) preceded the onset of gesture limb marker movement. Onset of segmental movement of the gesture limb followed a proximal to distal order (T1 = knee, T2 = toe), and a distal to proximal order at movement termination (T3 = toe, T4 = hip). Trunk translation (T5 = ASIS) followed gesture limb marker termination to complete the sequence (returning to first position).

Total movement time did not differ between groups, indicating they achieved the overall temporal goal of the movement [Control: 1.17 sec (± 0.032), STG: 1.15 sec (± 0.022), PTB: 1.15 sec (± 0.025)]. Nevertheless, some differences in the manner in which they achieved the movement were found. A longer time between trunk translation and initiation of toe movement was observed in the ACL-reconstruction groups (Fig. 3). There were also delays between completion of toe movement and completion of movement at more proximal segments in the ACL-reconstruction groups.

ACL-reconstruction subjects displayed temporal delays between trunk and limb coupling of up to 0.10 seconds at movement onset and 0.11 seconds at termination, greater than control subjects. Specifically, STG subjects were delayed in initiating movement at the toe, compared to controls [$F(2,13) = 3.74$, $p < 0.05$; post hoc Control vs. STG $p < 0.01$]. At movement termination, STG subjects were delayed at the knee, as well as at the trunk, compared to controls. [Knee: $F(2,13) = 11.64$, $p < 0.01$; post hoc STG vs. Control $p < 0.01$, and STG vs. PTB $p < 0.01$. ASIS: $F(2,13) = 4.03$, $p < 0.05$; post hoc Control vs. STG $p < 0.05$].

Representative profiles of hip and knee angular velocity of the gesture limb of a subject from each group are presented in Figure 4. The first peak in velocity at each marker occurred during ascent of the gesture limb. The second peak occurred during descent to first position. In contrast to the smooth, bell-shaped velocity profile of the control subject (Fig. 4A), the velocity profiles of the involved limb of the STG (Fig. 4B) and PTB subjects (Fig. 4C) were multi-modal. Additionally, in both of the ACL-reconstruction subjects, the angular velocity of the hip and knee were reduced during both ascent and descent, compared to controls. Furthermore, there were significantly more movement units at the knee for both ACL-reconstruction groups on the involved limb (STG: mean 2.50 ± 0.23; and PTB: mean 2.01 ± 0.14) as well as on the uninvolved limb (STG: mean 2.32 ± 0.17; and PTB: mean 2.11 ± 0.20) compared to the control group on both the non-pre-

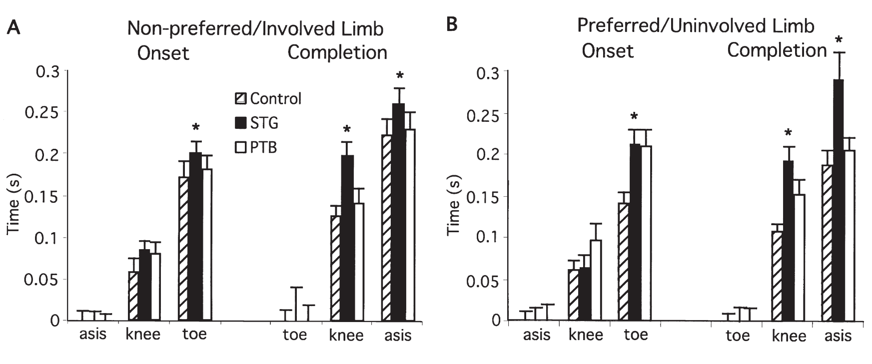

Figure 3 **A**, Mean (± SE) displacement onset and termination times (relative to the marker which began or ceased moving first) of the non-preferred limb in control (white) and involved limb in STG (diagonal hatching) and PTB (black) groups. **B**, Mean (± SE) displacement onset and termination times of the preferred limb in control and uninvolved limb in STG and PTB groups.

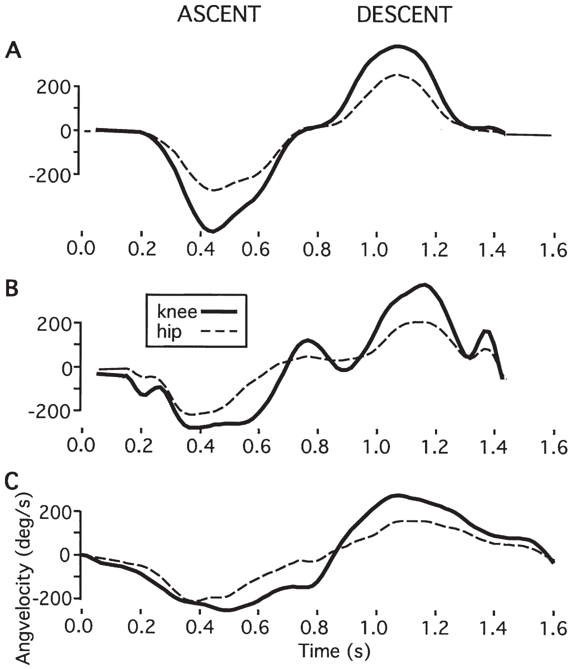

Figure 4 Representative hip and knee angular velocity profiles of the gesture limb for a subject from each group, with all traces aligned to the temporal (x) axis. The ascent and descent phases are indicated. **A**, control subject - non-preferred limb; **B**, STG subject - involved limb; **C**, PTB subject - involved limb.

ferred (mean 1.31 ± 0.13) and preferred limbs (mean 1.29 ± 0.10) (involved Knee: H= 10.21, X^2 = 5.99, $p < 0.05$; and uninvolved Knee: H= 9.66, X^2 = 5.99, $p < 0.05$). This was also the case at the hip for both ACL-reconstruction groups on the involved limb (STG: mean 2.69 ± 0.29; and PTB: mean 2.32 ± 0.19) as well as the uninvolved limb (STG: mean 2.53 ± 0.18; and PTB: mean 2.38 ± 0.18) compared to the control group on both the non-preferred and preferred limbs (mean 1.25 ± 0.18; and mean 1.23 ± 0.15, respectively) (involved Hip: H= 7.92, X^2 = 5.99, $p < 0.05$; and uninvolved Hip: H= 10.52, X^2 = 5.99, $p < 0.05$). There were no difference between ACL reconstruction groups.

The differences observed in the velocity profiles during the ascent phase were reflected in slower mean peak angular velocity values at the involved hip and knee of both ACL-reconstruction groups (Fig. 5 A and B). At the involved hip, STG subjects were significantly slower (246°/sec ± 34°/sec) than control subjects (283°/sec ± 35°/sec); [$F(2,13)$= 3.83, $p <$ 0.05; Control vs. STG $p < 0.05$]. PTB subjects did not differ from either group (266°/sec ± 24°/sec). At the knee, STG and PTB subjects moved at comparable speeds (384°/sec ± 59°/sec vs. 391°/sec ± 52°/sec, respectively), but were significantly slower than control subjects (460°/sec ± 33°/sec); [$F(2,13)$ = 7.91, $p < 0.01$].

ACL-reconstruction groups spent less time in deceleration during the ascent phase of the movement compared to controls, on both involved and uninvolved limbs, as seen in Fig. 5 C and D. Control subjects spent 57% of the ascent phase in deceleration (± 0.01), compared to STG subjects who spent 48% (± 0.008), and PTB subjects who spent 47% (± 0.007); [$F(2,13)$ = 6.62, $p < 0.05$; post hoc Control vs. STG and Control vs. PTB $p < 0.05$]. Thus, despite the lower peak velocities in the ACL-reconstruction groups, similar movement times were achieved by increasing the time spent accelerating the limb. Differences between groups in temporal coordination (onset and termination times), mean peak angular velocity, and percent deceleration time were not reflected in differences in variability (CV) measures ($p > 0.05$ in all cases).

Discussion

Despite appearing visually similar, the involved gesture limb of subjects with ACL reconstruction displayed slower peak velocities compared to the control group. Bilateral temporal alterations were present in the movement of those with ACL reconstruction, such as temporal delays between trunk and limb at movement onset and termination, and decreased percent deceleration (relative timing). Velocity profiles were less smooth in ACL-reconstruction subjects, manifested by increased number of movement units. Overall, these findings suggest that there are differences in gesture limb temporal kinematics following ACL injury, reconstruction, and rehabilitation.

Trunk and Limb Timing

The trunk was the first segment to move and the last to stop when performing the passé. This movement pattern was similar to that observed in other voluntary movements which begin and end with a postural adjustment.[32-34] However, subjects that had undergone ACL reconstruction displayed bilateral delays in initiation of movement at the distal extremity (toe), and delays in completion of movement at more proximal segments (knee and ASIS); thus supporting our hypothesis of less tightly coupled trunk and limb movement. Delays were, in some instances, quite substantial (up to 110 msec), considering that both the passé ascent and descent phases were only 600 msec in length. These delays were greatest on the uninvolved gesture limb in the STG group. Perhaps this was due to a more cautious control strategy on the part of STG subjects for weight shift and acceptance, particularly onto the operated stance limb. Movement onset and termination temporal coupling on both limbs of PTB subjects more closely resembled that of controls. Whether this "cautious" control strategy existed prior to or was a re-

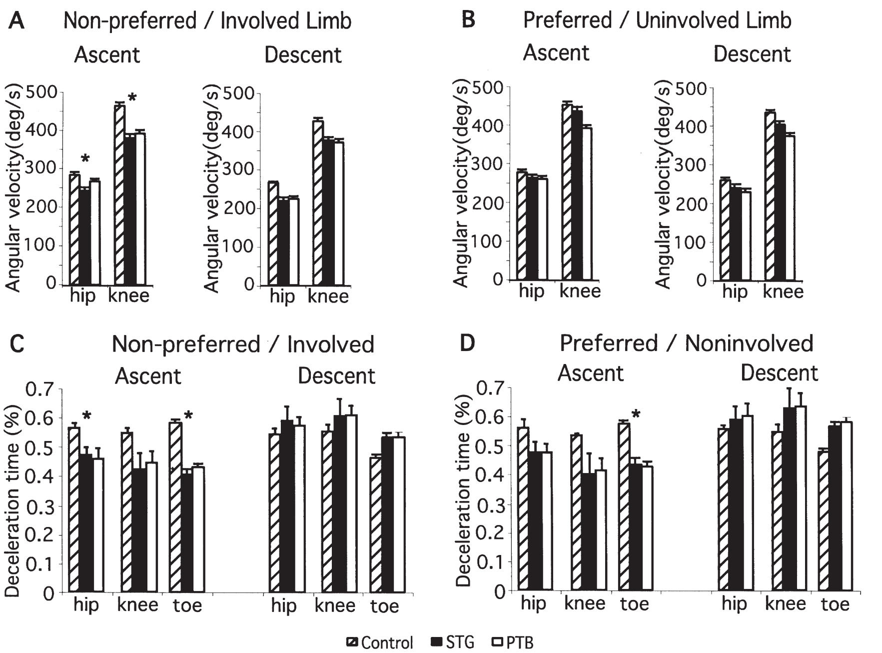

Figure 5 Histograms **A** and **C** represent the non-preferred gesture limb of the control group and involved limb of the STG and PTB groups; **B** and **D** represent the preferred gesture limb of the control group and uninvolved limb of the STG and PTB groups. **A**, Mean (± SE) peak angular velocity of the non-preferred limb in control (white) and involved limb in STG (diagonal hatching) and PTB (black) groups. **B**, Mean (± SE) peak angular velocity of the preferred limb in control and uninvolved limb in STG and PTB groups. **C**, Mean (± SE) deceleration time of the non-preferred limb in control and involved limb in STG and PTB groups. **D**, Mean (± SE) deceleration time of the preferred limb in control and uninvolved limb in STG and PTB groups.

sult of the ACL injury and surgery is unknown.

The bilateral alteration in proprioception and postural control seen in ACL-reconstruction subjects (as well as subjects with ACL deficiency), despite proprioception and agility rehabilitation training, suggests that central control mechanisms adapt to the loss of proprioceptive inflow from the ACL.[22,35,36] Input about joint position and speed are important factors in organizing postural control. Our findings of temporal delay on both limbs in the STG group support this concept of adaptive central control mechanisms,[22] resulting in more conservative and protective movement strategies.

Movement Smoothness

Since dancers aspire to move with grace, we examined the smoothness of the gesture limb. Dancers in the control group displayed smooth unimodal (bell-shaped) velocity profiles at the hip, knee, and toe. Multimodal velocity profiles (increased number of movement units) were seen at the hip and knee of both limbs in both ACL-reconstruction groups. One reason for multi-modal joint motion is unstable control of the joint dynamics.[37] While this study is limited to two-dimensional kinematics, the increased number of movement units in ACL-reconstruction hip and knee velocity profiles suggest that kinetic analysis would find altered joint torques.

Altered control of gesture limb motion was also measured in different acceleration to deceleration ratios. During the ascent phase of the passé movement, ACL-reconstruction subjects spent less time in deceleration. (Ratios comparing acceleration to deceleration were similar between groups in the descent phase.) This decrease in deceleration time occurred for both involved and uninvolved limbs. The decreased time spent in deceleration during ascent may reflect a compensatory strategy by dancers with ACL reconstructions to achieve the appropriate temporal goals of the passé despite the decreased peak velocities measured at the hip and knee. A longer acceleration period may reflect problems in generating forces to lift the gesture limb against gravity during the ascent phase.

While increased movement variability, as measured by CV, is frequently seen in populations with problems in motor control,[38] there were no differences in variability between groups. The kinematic solutions used by dancers with ACL reconstruction in this study were consistent. We interpret this to mean that these kinematics reflected well-integrated movement solutions to the altered state of the system.

Single Joint Versus Functional Movement

Despite knee range of motion and strength, which met criterion for discharge, dancers with ACL reconstruction displayed reduced angular velocities at the involved knee while performing the passé. In this study, isokinetic testing at 90°/sec revealed deficits in both ACL reconstruction groups in quadriceps mean peak torque. Perhaps the quadriceps deficits indicated by the isokinetic tests are partially the cause of the impairment observed kinematically. However, isokinetic values only reflect impairment of single joint motion and are not a direct correlation with function.[25]

The knee activity scores indicated that the reconstructed dancers did not consider themselves able to do all activities fully. Although they looked normal and could perform professionally, these reconstructed dancers were still aware of subtle differences in performance. We selected this athletic outcomes questionnaire as the most relevant for this population because there was no dance-specific tool available. Although correlations between isokinetic tests, arthrometry, functional performance tests (such as triple hop test), and activity outcomes questionnaires have been found,[6,25,39] these correlations (r = 0.31 to 0.70), suggest that factors besides "strength" must contribute to performance deficits. This reinforces the need for function-specific tools in assessing outcomes.

Functional movement is rarely restricted to motion about one joint. Rather, it involves synchronized motion of two or more joints. Therefore, it is important to understand the impact of joint injury on the joints surrounding it. In addition to reduced angular velocity at the involved knee, dancers with ACL reconstruction displayed reductions in angular velocity at the hip. This indicates that impairment at the knee also affected the hip because these joints often move together.

The segmental relationship of the hip and knee in performance of the passé affects bi-articular muscle length and their effective moment arms. Changing the hip angle has a greater effect on biceps femoris length than changing the knee angle; while the reverse is true for the rectus femoris, but to a lesser degree.[40] Hip and knee flexion during the ascent phase of the passé requires proximal shortening and distal lengthening of the rectus femoris and the reverse for the hamstrings. Therefore, during the ascent phase of the passé, the primary action is concentric contraction of the rectus femoris (and iliopsoas) to flex the hip and the hamstrings to flex the knee. The passé movement may be relatively more challenging for the STG group. Selection of the semitendinosus-gracilis tendon complex as a graft may impose greater demands on the biceps femoris during the passé in which control of knee flexion is a critical component. Selection of the central third of the patella tendon as a graft may impose greater demands on the rectus femoris when knee extension and weightbearing activities are of critical importance.

Clinical Implications

Currently, the focus of rehabilitation is to return dancers to pre-injury levels of performance. The results of this study document the presence of bilateral adaptations in gesture kinematics of limbs after undergoing ACL reconstruction. It is possible that control of complex movements may never return to pre-injury status but must reorganize to reflect an altered neuromuscular system. This represents a shift from current thinking toward peripheral orthopaedic injury and may warrant some restructuring of current rehabilitation protocol such as placing even greater emphasis on postural control training.

The selection of STG grafts in dancers has been suggested to minimize patella-femoral problems following ACL reconstruction and to achieve the aesthetics of genu recurvatum. For most parameters we did not find any differences between STG and PTB groups. However, there were greater temporal delays in trunk-toe coupling in the STG group compared to the PTB and control groups, which would not justify selection of the STG graft over that of the PTB. While small sample size did not allow us to determine other differences between the ACL-reconstruction groups, this remains an interesting topic for further study. Since this study focused on a specific movement pattern, findings may be limited to the dance-specific non-weightbearing movement under analysis. Furthermore, it is possible that individuals who sustain ACL injury perform differently, predisposing them to this kind of injury.[36] Until researchers are able to easily follow large numbers of individuals prospectively, this remains conjecture. Kinematic, kinetic, and EMG analysis of other dance-specific movements is warranted to better assess movement outcomes following ACL reconstruction.

Conclusion

This study provides kinematic evidence of altered movement organization after ACL reconstruction. While we cannot conjecture whether the original ACL injury or the ACL reconstruction had a more profound effect, our results support the concept that motor patterns adapt to changes in the state of the system despite restoration of mechanical stability. Development and use of dance-specific outcome measures might assist in ascertaining as well as maximizing functional outcomes in this population. Further kinematic and kinetic analyses of dance movement will assist in understanding changes that occur following injury.

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