Knee Surg, Sports Traumatol, Arthrosc
(2000) 8:262–269

KNEE

DOI 10.1007/s001670000130

K. S. Rudolph
M. J. Axe
L. Snyder-Mackler

Dynamic stability after ACL injury: who can hop?

Received: 17 January 2000
Accepted: 25 May 2000

K. S. Rudolph · M. J. Axe
L. Snyder-Mackler (✉)
Department of Physical Therapy,
University of Delaware,
McKinly Lab,
Newark, DE 19716, USA
e-mail: smack@udel.edu
Tel.: +1-302-831-3613
Fax: +1-302-831-4234

Abstract Single-leg hops are used clinically to assess knee function in patients following anterior cruciate ligament (ACL) rupture and reconstruction. Researchers study ACL-deficient individuals in order to identify movement strategies in the absence of a major knee stabilizer, thereby providing information to clinicians regarding treatment options. Single-leg hops represent an activity which places higher demands on the knee than walking or jogging. Hops are thought by some to represent demands that are more comparable to those found during high level sports. Therefore hopping might provide more information about knee stability during dynamic activities than less strenuous activities. This paper reflects one component of a larger study involving comparisons of joint motions and muscle activity patterns in uninjured individuals (*n*=10) and two groups of athletes who had complete ACL ruptures; one group had substantial knee instability (noncopers, *n*=10), and the other had no signs of knee instability (copers, *n*=11). In this paper we report the findings from the single-leg hop activity. The results indicate that coper subjects move in a manner nearly identical to uninjured persons. Kinetic data suggest that copers stabilize their knees with greater contributions from the ankle extensor muscles. Muscle activity data demonstrate that there is no reduction in quadriceps femoris activity in the coper subjects. In the group of ten subjects with knee instability (noncopers) who participated in the overall study involving walking, jogging, hopping, and a step activity only four were willing to hop. Work in our laboratory has established that when high level athletes rupture their ACL, the majority of them cannot return to high level sports. The small number of noncopers in this study who were willing to hop supports our previous findings. Those noncopers who did hop displayed reduced knee range of motion and external knee flexion moments, a movement strategy remarkably similar to that found during other activities. Neither the copers nor the noncopers showed evidence that quadriceps activation was diminished.

Keywords Anterior cruciate ligament · Hop · Kinematics · Kinetics · Electromyography

Introduction

Knee instability in anterior cruciate ligament (ACL) deficient persons has traditionally been assessed using static measures (passive anterior tibiofemoral joint laxity, presence of pivot shift); however, knee instability during dynamic activities is not related to passive measures [5]. The need for a measure of the degree of dynamic knee instability led Noyes et al. [15] to develop a series of hop tests to allow clinicians to compare the performance of the injured limb to the uninjured limb in persons with ACL deficiency. They reported that side-to-side hop symmetry less than 85% indicates diminished knee function that is related to quadriceps femoris weakness and patient self-assessment of difficulty with pivoting movements. Hop symmetry is now used as a standard measure of knee function in ACL-deficient individuals [8]. Hop tests have also been used to predict potential to succeed in nonoperative management [6] and to advance patients to sport specific rehabilitation activities following ACL reconstruction [14]. Researchers use single-leg hop tests to study knee function in ACL-deficient persons [6, 8, 14, 16] particularly because hopping is more challenging than walking or jogging and is thought by some to more closely represent the demands of high level sports.

The primary objective in studying movement and muscle activity patterns in ACL-deficient individuals is to identify mechanisms that contribute to *dynamic* knee instability so that specific treatment programs can be developed. Unfortunately, results of many studies of movement strategies of ACL-deficient persons have been contradictory. Investigators who have studied kinematics and kinetics report reduced external knee flexion moments and often infer that the reduced moment represents lower quadriceps femoris activity in those with ACL deficiency [1, 9, 11, 19] (K.S. Rudolph et al., submitted); however, electromyographic (EMG) data are often absent to confirm that inference. In a widely cited study, Berchuck et al. [1] suggested that the reduced external knee flexion moment indicates reduced quadriceps femoris activation. They hypothesized that ACL-deficient individuals reduce their quadriceps femoris contraction because a strong contraction is presumed to cause excessive anterior tibial translation, which could result in an episode of giving way. Studies of EMG activation have not supported this interpretation. Lass et al. [13] found earlier onset and longer duration of quadriceps activity but no difference in the level of quadriceps activation in ACL-deficient individuals during level and inclined walking. Kalund et al. [12] found no difference in quadriceps activation but found earlier onset of hamstring muscles in ACL-deficient persons during level and inclined walking. Cicotti et al. [2] reported increased vastus lateralis activity and early hamstring muscle onset during walking and stair ascent and descent in ACL-deficient subjects.

The danger in inferring muscle activity from external moments is that moments are *net* moments and therefore represent the sum of moments generated by opposing muscle groups. A reduced external knee flexion moment may represent reduced knee extensor activity, but there is an equal chance that it represents increased knee flexor activity. The results of investigations during walking and jogging trials in our own laboratory shed light on the mechanism underlying the reduced external knee flexion moment (K.S. Rudolph et al., submitted). In this study kinematic, kinetic, and EMG data were studied in the same copers, noncopers, and uninjured subjects who participated in the current study. The results of this work indicate that the reduced knee flexion moment is related to an increase in hamstring activity rather than a decrease in quadriceps activity, demonstrating the importance of investigating movement and muscle activation simultaneously (K.S. Rudolph et al., submitted). The results also showed that only in the noncoper subjects is the reduced external knee flexion moment related to quadriceps femoris weakness. Unfortunately, it is not possible to determine the precise relationship between force and EMG levels during dynamic activities. When muscle weakness is present, it is possible for muscle activation levels to be higher than expected since a greater proportion of the muscle fibers might be activated to resist a given load. The relationship between quadriceps femoris weakness and reduced external knee flexion moment, however, may indicate that although quadriceps activation is high, the force generating capability of the muscle associated with a given level of activation may not be sufficient adequately to stabilize the knee in the noncoper subjects.

It is likely that in addition to methodological differences some of the inconsistent findings reported in the literature have resulted from the failure of investigators to consider the degree of dynamic knee stability in the subjects tested. Knee stability is traditionally assessed using static measures such as passive anterior knee joint laxity or pivot shift tests; however, static measures do not predict *dynamic* stability [5]. Some individuals with a very small degree of passive joint laxity experience profound knee instability (including giving way) while others have large passive knee laxity measures with no signs of knee instability, even during highly challenging athletic activities [4, 5, 15]. It is reasonable to expect that ACL-deficient subjects with poor dynamic stability would have different movement and muscle activity patterns than those with good knee stability. Inclusion of subjects based purely on "complete ACL rupture," without regard to functional ability, may result in subject samples that include persons with very different movement strategies. If subjects are categorized based on their knee stability during *dynamic* activities, it is likely that more consistent differences in movement patterns will emerge between stable and unstable ACL-deficient subjects as well as uninjured persons.

The goal of our research was to study individuals with excellent dynamic knee stability (copers) to gain information regarding successful stabilization strategies, and to study ACL-deficient subjects with poor dynamic knee stability (noncopers) to gain information regarding unsuccessful, and potentially harmful, stabilization strategies. In this study we classified ACL-deficient persons based on dynamic stability measures (including subjective reports of knee function, functional activities, as well as the number of episodes of giving way), rather than traditional static clinical measures (such as passive laxity and presence of a pivot shift). After classifying the subjects as having excellent or poor knee stability we studied their movement patterns during four activities of varying difficulty, walking, jogging, a step activity, and single-leg hopping. In this paper we report the results of the hop trials. We hypothesized that when individuals are classified based on dynamic functional ability, more pronounced movement adaptations would occur in ACL-deficient subjects with documentation of poor knee stability, but that subjects with excellent knee stability would move much as uninjured individuals. We also expected that neither the copers or noncopers would reduce the quadriceps muscle activation, and that the ability to stabilize the knee would be unrelated to passive joint laxity and partially related to quadriceps femoris strength.

Methods and materials

Subjects

All subjects were athletes who participated regularly in level I sports (involving jumping, pivoting, and hard cutting) and level II sports (involving lateral motions) [4] and gave informed consent, which was approved by the Human Subjects Review Board at the University of Delaware. Eleven copers were tested (two women, nine men; ages 22–43 years, mean 30.7). Copers were operationally defined as high-level athletes who had been ACL-deficient for at least 1 year (confirmed by magnetic resonance imaging, MRI, or with >3 mm side to side laxity measurements [3]) without any knee instability during regular participation in level I and II sports. Copers could have had no more than one episode of giving way, even during sports, since injury. The copers were recruited from a group of individuals who had been identified from the community, some of whom had participated in previous research in our laboratories. Ten individuals, who had been participating in high-level sports prior to injury and were within 8 months of ACL rupture (confirmed by MRI), were recruited as noncopers with consent from their physician. Patients who had ruptured the ACL but had not participated regularly in high-level sports prior to injury or those who had a repairable meniscal tear were not included in the study. In order to be classified as a noncoper subjects had to demonstrate knee instability during activities of daily living (since the noncopers had not yet returned to sports).

To demonstrate knee instability objectively, potential noncopers underwent a screening evaluation of dynamic knee function based on the work of Fitzgerald et al. [6]. The screening tests (with cutoff criteria) were: four hop tests (<80% timed hop); Knee Outcome Survey–Activities of Daily Living Scale (<80%) [10]; global rating scale (<60% of prior knee function); episodes of giving way (more than two since injury). If subjects met any *one* of the above criteria they were considered to have dynamic knee instability and classified as noncopers. Ten noncopers (four women, six men; ages 16–43 years, mean 28.1) were recruited for the study. Ten uninjured individuals, who were matched by age and activity level to the coper subjects (two women, eight men; ages 23–41 years, means 32.2), also participated in the study. All ACL-deficient subjects had full range of motion in both knees, no visible or palpable knee effusion, had no symptoms of locking, and had an uninvolved knee that was healthy. Subjects who had undergone previous meniscectomies were included.

Quadriceps strength and knee joint laxity testing

Quadriceps femoris muscle strength was measured bilaterally using a maximum voluntary isometric contraction (MVIC) with burst superimposition as described previously [18]. The MVIC of each leg was recorded and a quadriceps index was calculated (involved MVIC/uninvolved MVIC×100). Passive anterior knee joint laxity was measured using a KT-2000 arthrometer (Medmetrics, San Diego, Calif., USA). The anterior laxity was reported as the difference in laxity from side-to-side (involved minus uninvolved). Daniel et al. [3] have reported that a side-to-side difference greater than 3 mm confirms ACL rupture in 99% of cases.

Muscle activity

Electromyographic data were recorded from the lateral hamstrings, vastus lateralis, soleus, and medial head of the gastrocnemius muscles of both limbs using surface electrodes and an eight channel FM radio telemetry system (B&L Engineering, Santa Fe Springs, Calif., USA) at 960 Hz. A linear envelope of the EMG from each muscle was created by full-wave rectification and low pass filtering the data (second-order, phase-corrected, Butterworth filter) with a cutoff frequency of 20 Hz. Electromyographic data were collected from each muscle group during two 2-s MVICs. The MVIC was performed with the subjects positioned on a padded table with the reference limb secured to the table with a padded cuff and steel chains in the following testing positions: vastus lateralis: hips flexed 90°, knee flexed 60°; lateral hamstrings: prone on the table with the knee flexed 20°; soleus: kneeling on hands and knees with hips and knees flexed 90°, ankles in a neutral position; gastrocnemius: prone on the table with hips, knees and ankles in a neutral position. The EMG was recorded after the maximum effort was achieved. Resting EMG was also collected for each muscle group. One limitation of using isometric efforts to determine maximum EMG levels is that isometric contractions do not take into account force-velocity and length-tension relationships in the muscles. It is not unusual therefore to see EMG levels during dynamic trials that exceed those recorded during maximum isometric efforts. In order to determine the maximum activation for the subjects in this study all trials in the larger comprehensive study that all subjects performed (walk, jog, and step trials) were examined for the peak EMG activity over a 30-ms interval. The peak EMG activity over 30-ms from either the dynamic or maximum isometric trials was used to normalize the EMG data in the dynamic trials.

Three-dimensional motion analysis

Kinematic data were collected from a six-camera, three-dimensional motion analysis system (Vicon, Oxford Metrics, London, UK). The cameras were calibrated using a calibration volume of 1.5×0.5×0.70 m, and calibration errors were held below 1.5 mm. Kinematic data were collected at a sampling rate of 120 Hz and low-pass filtered (fourth-order, phase-corrected Butterworth filter) at 10 Hz. Force data were recorded from a six-component force platform at a rate of 960 Hz (Bertec Corporation, Worthington, Ohio, USA). Joint motions and external moments were calculated from retroreflective markers (located on the pelvis, and bilaterally on the thighs, shanks, and feet) and force platform data with Move3d software (MOVE3D, NIH Biomotion Laboratory, Bethesda Md., USA). Ground reaction forces were normalized to body weight (% BW) and joint moments were normalized to body mass (Nm/kg) to reduce intersubject variability. Five trials were performed on each leg in which subjects were asked to hop onto and immediately off of the force platform. We used the following discrete events of the hop cycle to analyze the movements: initial contact (IC, when vertical force exceeded 50 N), transition to hop propulsion (the point at which the ground reaction force in the line of progression changed from a negative breaking force to a positive propulsive force), peak knee flexion, and peak knee extension. Hop length, determined by the location of a marker placed on the subjects heel, was used to calculate the hop quotient [(involved hop length/uninvolved hop length)×100]. Data were averaged over the five trials.

Kinematic and kinetic data were analyzed during the ground contact phase of the hops. Joint moments were used to calculate the "support moment" which is the sum of the internal extensor moments at the hip, knee, and ankle [21]. Winter et al. [21] have postulated that the distribution of support moment about the hip, knee, and ankle indicates the ability of the nervous system to adapt to different external demands on the body. The relative contribution of each joint to the support moment (% support moment) was determined by dividing each internal extensor moment by the total support moment.

In addition to muscle timing variables, muscle intensity was evaluated by integrating the linear envelope of the EMG curves over a weight acceptance interval. Weight acceptance was defined as the range from 100 ms prior to initial contact (to account for electromechanical delay [20]) to the point of peak knee flexion. This interval was chosen because it is the interval at which a strong quadriceps femoris contraction occurs, thereby creating the greatest potential for knee instability. Muscle cocontraction was assessed, using the normalized EMG data, between the vastus lateralis and lateral hamstrings and between the vastus lateralis and medial gastrocnemius using an equation developed in our laboratory. We operationally defined cocontraction during weight acceptance as the simultaneous activation of two muscles using the following equation: EMGS/EMGL×(EMGS+EMGL), where EMGS is the level of activity in the less active muscle and EMGL the level of activity in the more active muscle (to avoid dividing by zero errors). This ratio was multiplied by the sum of the activity found in the two muscles. This method provided a sample-by-sample estimate of the relative activation of the pair of muscles as well as the magnitude of the cocontraction over the entire hop cycle. The cocontraction curve was integrated over the weight acceptance interval and used in the analysis. Using this equation, high cocontraction values represent a high level of activation of both muscles across a large time interval, whereas low cocontraction values indicate either low level activation of both muscles, or a high level activation of one muscle along with low level activation of the other muscle in the pair. Low cocontraction values represent more selective activation of muscles whereas large coactivation values represent a more generalized muscle activation. High-level cocontraction of opposing muscle groups could result in higher joint compression [17]. The higher joint compression, along with damage caused by the shear forces associated with tibiofemoral translation in an unstable knee [17] would not bode well for long-term joint integrity.

A one-way repeated measures analysis of variance was used to determine the statistical significance of differences between groups (coper, control) and between sides (repeated measure: involved vs. uninvolved; Systat, Evanston, Ill., USA). Post-hoc testing was performed with paired *t* tests with Bonferonni correction. Regression analyses were performed to investigate relationships among relevant variables. The level of $P<0.05$ was set for statistical significance.

Results

Ten subjects were identified by the screening procedure as noncopers and agreed to participate in the comprehensive study of movement patterns (walking, jogging, hopping, and ascending/descending a step). The passive joint laxity in the ten noncopers did not differ than that in the 11 copers (copers: 3–7 mm, mean 5.1±1.48; noncopers: 5–12 mm, mean 6.75±3.50; $t=0.894$, $P=0.382$). Quadriceps indices were higher in the 11 copers ranging from 74.8% to 126% (97.1±12.7%) than in the 10 noncopers, whose quadriceps indices ranged from 62.4% to 97.3% (75.3±11.3%; $t=3.983$, $P=0.001$). Hop quotients did not differ between the copers (95.8±5.3%) and uninjured subjects (93.7± 9.0%; $t=0.645$, $P=0.527$); both were within normal ranges for side-to-side symmetry [16].

Of the ten noncopers who participated in the comprehensive study, only four (40%) consented to perform the hop portion of the study. Despite encouragement, six of the noncoper subjects refused to participate in the hop only because of fear of further damaging their knee, although they did complete the remainder of the activities in the comprehensive study (results presented elsewhere). The small number of noncopers who were willing to hop prevented statistical comparison between copers and controls, and therefore any differences observed in the noncoper subjects are presented descriptively. In an attempt to ascertain the factors involved in the willingness to hop we compared the four noncopers who hopped to the six who did not. Those noncopers who declined to hop had joint laxity measures of 3–9 mm (mean 5.3 mm) and quadriceps indices of 62.5–97.3% (74.05%) while those who did perform the hop trials had joint laxity measures of 5–12 mm (6.75 mm) and quadriceps indices of 65.8–84.9% (77.8%). Although statistical analysis was not performed on these data the noncopers, all appeared to have similar quadriceps indices and passive joint laxity.

Copers vs. uninjured subjects

Very few differences were observed between the copers and uninjured subjects in the kinematic, kinetic, or EMG variables. The only point in the hop cycle at which differences were observed was at the transition to hop propulsion during the ground contact portion of the hop cycle (see Table 1). There was a trend toward less hip flexion on both sides, and less knee flexion on the involved side in copers than in uninjured subjects. Copers also had less ankle dorsiflexion on the involved side than on their own uninvolved sides. The external hip flexion moment was lower in both limbs of the copers. The distribution of support moment about the hip, knee, and ankle showed that copers used a significantly higher contribution from the ankle ($F=8.595$, $P=0.009$) and showed a trend toward lower contribution from the hip ($F=3.806$, $P=0.066$) to the total support moment on both sides than control subjects (Fig. 1). No differences in vertical ground reaction force were observed between copers and uninjured control subjects.

No statistical differences were observed in the vastus lateralis activity between copers and controls (Fig. 2). A trend was seen among copers toward earlier termination of the

Table 1 Kinematic, kinetic and EMG data at the transition to hop propulsion (means and standard deviations)

Variable	Coper		Uninjured		
	Involved limb	Uninvolved limb	Left limb	Right limb	
Hip flexion angle (°)	44.3 ±2.7	43.3 ±1.8	49.3 ±2.8	49.4 ±1.9	*F*=3.560, *P*=0.075
Knee flexion angle (°)	46.7 ±2.8	49.8 ±2.1	50.8 ±2.9	52.2 ±2.2	*F*=4.501, *P*=0.060
Ankle dorsiflexion angle (°)	14.7 ±1.6	18.5 ±1.0	15.2 ±1.7	16.0 ±1.1	*F*=12.681, *P*=0.005
External Hip flexion moment (Nm/kg)	2.175±0.31*	1.977±0.23*	2.77 ±0.33	3.052±0.24	*F*=5.439, *P*=0.031*
Vastus lateralis termination (% stance)	0.761±0.021	0.762±0.019	0.800±0.023	0.819±0.020	*F*=3.532, *P*=0.076

*$P<0.05$, side difference in copers

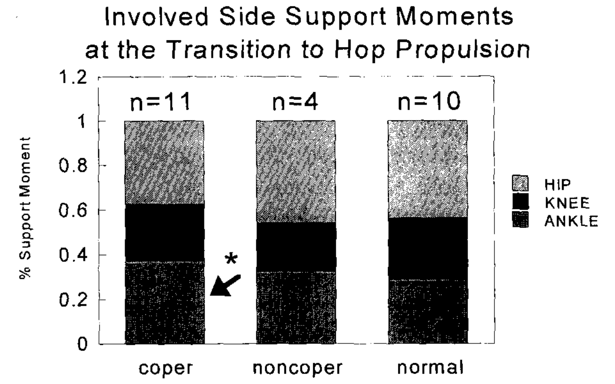

Fig. 1 Support moments on the involved side. *$F=8.595$, $P=0.009$

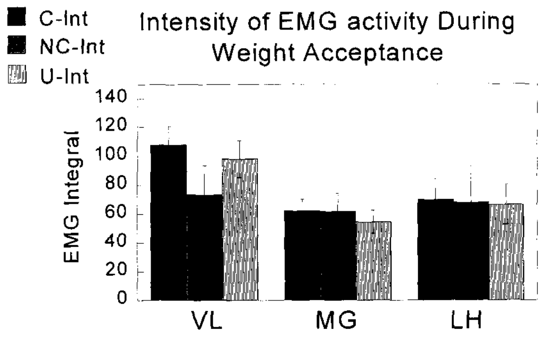

Fig. 2 Intensity of EMG activity during weight acceptance, from 100 ms prior to initial contact to the point of peak knee flexion

vastus lateralis activity on the involved side than the uninjured subjects at the end of the ground contact phase of the hop (Table 1).

Relationship between hop quotient and movement patterns

There was a significant correlation between the hop quotient and knee moment at peak knee flexion in uninjured subjects ($r=0.719$, $P=0.019$) but not in copers ($r=0.020$, $P=0.958$). Regression analyses revealed that in the uninjured subjects 83.1% of the variance in the hop quotient was accounted for by the variance in the knee moment at peak knee flexion, the level of EMG activity in the medial gastrocnemius around initial contact, and the amount of vastus lateralis and medial gastrocnemius cocontraction ($F=9.868$, $P=0.010$) whereas the hop quotient in copers showed no such relationship ($F=0.045$, $P=0.986$). In contrast, copers showed a strong relationship between hop quotient and the level of EMG activity in the soleus muscle around initial contact and the external hip flexion moment at peak knee extension, with 68.8% of the variance in the hop quotient accounted for by the variance in the hip moment ($F=6.619$, $P=0.030$).

The copers had normal knee extension moments during weight acceptance, which was related to the level of EMG activity, with 83.5% of the variance accounted for by the level of EMG activity in the soleus and vastus lateralis as well as the level of cocontraction between the vastus lateralis and lateral hamstring muscles ($F=10.108$, $P=0.009$).

Noncopers

Conclusions from the four noncopers who hopped are limited and should not be taken to represent a comprehensive analysis of how noncopers' hop; however, the four noncopers did appear to hop differently. Compared to

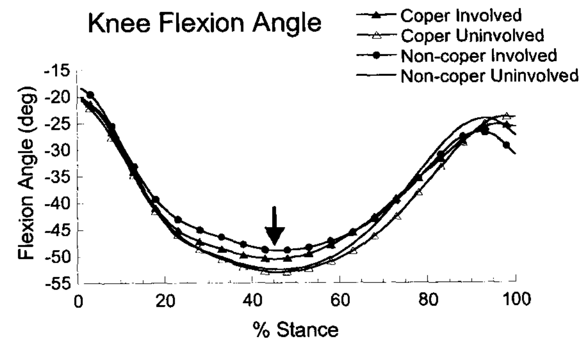

Fig. 3 Coper ($n=11$) and noncoper ($n=4$) knee angle during stance. Five trials were averaged for each subject. *Curves* represent the average across all subjects. *Arrow* point of peak knee flexion

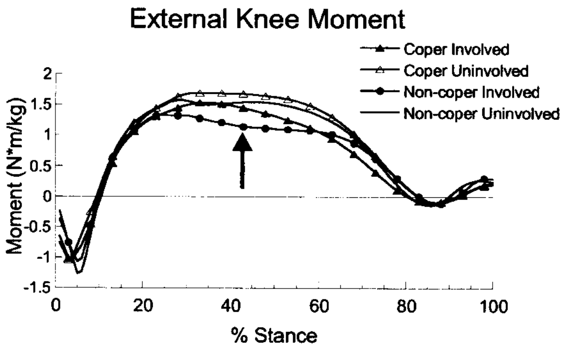

Fig. 4 Coper (n=11) and noncoper (n=4) knee moment during stance. Five trials were averaged for each subject. *Curves* represent the average across all subjects. *Arrow* point of peak knee flexion

copers and uninjured subjects, the four noncopers flexed less throughout the entire ground contact portion of the hop (Fig. 3) and had lower external knee extensor moments (Fig. 4) and lower peak vertical ground reaction forces (involved 1.845±0.153% BW, uninvolved 1.9030± 0.164% BW) than copers: (involved 2.474±0.092% BW; uninvolved 2.372±0.099% BW). The noncopers also had higher hip and lower knee contribution to the support moment at the transition from weight acceptance to hop propulsion (Fig. 1).

Discussion

The results of this study validate the use of hop tests as an appropriate clinical tool to assess dynamic knee function in ACL-deficient individuals by demonstrating that highly functional copers had normal hop symmetry while most of the noncopers were unwilling to perform the activity. The unwillingness to hop was unrelated to the amount of joint laxity and partially related to quadriceps strength. Those in the noncoper group as a whole were weaker than those in the coper group; however, three of the noncopers had quadriceps strength that was within normal ranges (85% of their uninvolved side). Only one of those three subjects consented to hop, indicating that quadriceps strength alone does not predict the subjects' willingness to hop.

Noyes et al. [16] reported that 67 patients with chronic ACL deficiency performed single-leg hops. Noyes et al. found that quadriceps strength was related to the percentage deficit scores on the single-leg hop test and recommended that hop tests be avoided in ACL-deficient subjects who have moderate to severe symptoms with activities of daily living and isokinetic strength deficits greater than 15%. Performing higher level activities, such as hopping, could be detrimental to unstable ACL-deficient individuals because evidence suggests that knee joint instability leads to accelerated joint degeneration. Setton et al. [17], studied the cartilage in ACL-deficient dogs and found that even relatively short periods of joint instability results in significant changes in the viscoelastic behavior of articular cartilage. Noyes et al. [15] reported a statistically significant relationship between extent of roentgenographic changes in the knee joint and joint swelling and giving way in chronic ACL-deficient individuals. This suggests that persons with knee joint instability, such as seen in our noncoper population, could experience accelerated joint degeneration and should be discouraged from performing activities in which knee instability would be elicited.

It should be stresses that the subjects reported by Noyes et al. [16] were chronically ACL deficient while the noncopers in our study had been injured more recently, had knee instability with daily activities, and had larger quadriceps deficits. The noncopers in our study were chosen because they represented the "worst of the worst" in terms of knee stability. They had instability even during their normal everyday activities and would therefore be the best subjects to reveal an unsuccessful stabilization strategy that could be addressed in rehabilitation. The fact that so few of the noncopers hopped indicates that this activity is too challenging for some ACL-deficient individuals, particularly if they have been recently injured. Studies on activities such as hopping rarely report the functional ability of the subjects, yet the results are often extrapolated to all ACL-deficient subjects. It is important to remember that if all of the subjects in a study hopped, one should suspect that the sample does not include subjects with a great deal of knee instability and therefore the results do not represent the entire ACL-deficient population.

The unwillingness to hop in the weaker, more unstable noncopers in our study supports the recommendation by Noyes et al. [16] that subjects with quadriceps weakness should not hop. Some noncopers with equal side-to-side strength did not hop while some noncopers with strength deficits greater than 85% did hop. This suggests that in the absence of quadriceps weakness the degree of dynamic knee instability experienced by the subject (rather than *passive* joint laxity) is another important factor when considering allowing a patient to return to higher level activities. It is interesting to note that one of the noncopers actually hopped farther on her injured knee (0.66 m) than on her uninjured knee (0.61 m), less than half the distance hopped by most other subjects, whose hop distances ranged from 0.91 to 1.84 m (mean 1.21 m). This demonstrates that the hop quotient alone may not capture the degree of diminished knee function in all individuals.

As we predicted, copers hopped in a manner remarkably similar to uninjured subjects. The lack of statistically significant differences is not related to the sample size of copers and uninjured subjects since power analyses revealed strong statistical power of 0.6911–0.7800 for kinematic and kinetic variables and 0.7390–0.9535 for EMG variables. The only differences between copers and uninjured subjects were observed at the transition to hop propulsion, where the copers remained more extended at the hip, knee, and ankle. The hip, knee, and ankle continued to flex beyond the transition to hop propulsion until peak knee flexion was achieved. A more extended position at a point in the range from initial contact to peak knee flexion may indicate a slower angular velocity. This is consistent with the findings of Gauffin and Tropp [7] who found decreased angular velocity at the knee in the ACL-deficient limb in persons with good knee stability during hopping.

The copers had lower external hip flexion moments and higher ankle support moments at the transition to hop propulsion, which may reflect a greater contribution to knee stability from the ankle extensors. This is supported by the regression analysis that identified the soleus integral as contributing to the variability in the hop quotient and the normal knee moment at peak knee flexion. Ankle extensors control tibial advancement and therefore also control knee flexion. In uninjured subjects, hop symmetry appears to be related most to the ability of these uninjured subjects to absorb forces at the knee since hop symmetry was significantly correlated with external knee flexion moment at peak knee flexion. In copers, however, hop symmetry is related more to the external hip flexion moment closer to the end of the hop propulsion phase. The lower hip extensor moment, along with the greater ankle support moment in the copers suggests that they are able successfully to transfer control away from the knee to the ankle to achieve normal hop symmetry.

Despite the larger support moments seen in the ankle extensors in copers there is no evidence that they avoid activating their knee extensors. At the end of the weight acceptance phase, however, copers did terminate the vastus lateralis activity earlier. At this point in the hop cycle the subjects were preparing for the next hop and the hamstrings were still active. Early termination of the quadriceps muscles may have allowed the hamstrings to stabilize the knee to a greater extent when the knee was entering a more extended position.

Because of the small number of noncopers who hopped we can only speculate as to the underlying movement pattern differences between copers and noncopers. However, those who did hop displayed movement patterns similar to those of noncopers seen in our own and other studies [1, 9, 11] (K.S. Rudolph et al., submitted). The noncopers tended to flex their knees less (stiffen the joint) and had lower external knee flexion moments throughout the entire ground contact portion of the hop, although they did not appear to reduce their quadriceps femoris activity. The reduced external knee flexion moment appears to be the hallmark of the ACL-deficient person with knee instability (noncoper) during lower level activities (walking) and highly demanding activities (jogging and hopping). During walking and jogging noncopers shift the distribution of support moments away from the knee to the hip (K.S. Rudolph et al., submitted). The lower knee support moment, in conjunction with a higher hip support moment in noncopers during hopping, suggests a similar strategy of joint stiffening and transfer of control to the hip that was the same pattern as that observed during walking and jogging. The stabilization strategies adopted by the noncopers during walking and jogging (K.S. Rudolph et al., submitted) are remarkably similar to those seen in the few subjects in this study who hopped. This suggests that noncopers rely on an invariable stabilization strategy rather than stabilization strategies to suit the demands of various tasks.

Had a task involving more than straightforward progression been used, more distinctly task-dependent strategies may have emerged; however, it is highly unlikely that the noncopers would have agreed to perform pivoting or cutting movements. One could argue that other factors contributed to the unwillingness of the majority of noncopers to hop, including motivation, joint impingement, and edema; however, all of the subjects in this study participated in high-level sports prior to injury and wished to return to them. As such, they were highly motivated to perform successfully. Subjects were excluded from the study if MRI revealed a repairable meniscal tear, or if they experienced symptoms of knee locking, had limited range of motion, or had visible or palpable swelling. The subjects also showed no signs of reflex inhibition in the quadriceps muscles since reflex inhibition would have been identified during the quadriceps femoris strength testing with burst superimposition. The dynamic instability that we report in this paper most likely refers to the feeling of giving way that is related to abnormal tibiofemoral movement (either full or partial giving way) that is related to inappropriate movement and muscle activation patterns rather than reflexive inhibition due to pain. It is also possible that although all of the noncopers were high-level athletes prior to their ACL rupture, the unwillingness to hop may have been related to not having participated in sports activities since the time of injury. This is unlikely, however, since nine of the ten noncopers in the original group of ten subjects had been tested less than 2.5 months after injury. Finally, the stiffening of the knee joint may also be related to quadriceps weakness, a finding which is currently being further investigated in our laboratory.

Acknowledgements This project was supported by the National Institutes of Health (Training Grant 5T32HD7490, Grant 1RO3HD3554701) the National Athletic Training Association (Grant 396E001), and the Foundation for Physical Therapy (Doctoral Research Award 97D12RUD01).

References

1. Berchuck M, Andriacchi TP, Bach BR, Reider B (1990) Gait adaptations by patients who have a deficient anterior cruciate ligament. J Bone Joint Surg Am 72:871–877
2. Ciccotti MG, Kerlan RK, Perry J, Pink M (1994) An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament deficient and reconstructed knee. Am J Sports Med 22:651–658
3. Daniel DM, Stone ML, Sach ML, Malcom L (1985) Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. Am J Sports Med 13:401–407
4. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR (1994) fate of the ACL injured patient. A prospective outcome study. Am J Sports Med 22:632–644
5. Eastlack ME, Axe MJ, Snyder-Mackler L (1999) Laxity, instability and functional outcome after ACL injury: copers versus noncopers. Med Sci Sports Exerc 31:210–215
6. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) A decision-making scheme for returning patients to high level activity with non-operative treatment after anterior cruciate ligament ruptures. Knee Surg Sports Traumatol Arthrosc 8:76–82
7. Gauffin H, Tropp H (1992) Altered movement and muscular activation patterns during the one legged jump in patients with and old anterior cruciate ligament rupture. Am J Sports Med 20: 182–192
8. Hefti F, Muller W, Hakob RP, Staubli H-U (1993) Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc 1:226–234
9. Hurwitz DE, Wolfensperger KB, Patel R, Kopinshi P, Bush-Joseph C, Bach BR, Andriacchi TP (1997) A relationship between quadriceps strength and function in patients with ACL reconstruction with a patellar tendon autograft. Trans Orthop Res Soc 22:654
10. Irrgang JJ (1998) Development of a patient reported instrument to assess outcome following knee injury. J Bone Joint Surg Am 80:1132–1145
11. Kadaba MP, Ramakrishnan HR, Gainey JC (1993) Gait adaptation in patients with anterior cruciate ligament deficiency. Trans Orthop Res Soc 18: 361
12. Kalund S, Sinkjaer T, Arendt-Nielsen L, Simonsen O (1990) Altered timing of hamstring muscle action in anterior cruciate ligament deficient patients. Am J Sports Med 18:245–248
13. Lass P, Kaalund S, leFevre S, Arendt-Nielsen L, Sinkjaer T, Simonsen O (1991) Muscle coordination following rupture of the anterior cruciate ligament. Acta Orthop Scand 62:9–14
14. Manal TJ, Snyder-Mackler L (1996) Practice guidelines for anterior cruciate ligament rehabilitation: a criterion based rehabilitation progression. Oper Techn Orthop 6:190–196
15. Noyes FR, Mooar PA, Matthews DS (1983) The symptomatic anterior cruciate-deficient knee. I. The long-term functional disability in athletically active individuals. J Bone Joint Surg Am 65:154–162
16. Noyes FR, Barber SD, Mangine RE (1991) Abnormal lower limb symmetry determined by functional hop tests after anterior cruciate ligament rupture. Am J Sports Med 19:513–518
17. Setton LA, Mow VC, Howell DS (1995) Mechanical behavior of articular cartilage in shear is altered by transection of the anterior cruciate ligament. J Orthop Res 13:473–482
18. Snyder-Mackler L, De Luca PF, Williams PR, Eastlack ME, Bartolozzi AR (1994) Reflex inhibition of the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am 76: 555–560
19. Tibone JE, Antich TJ, Fanton GS, Moynes DR, Perry J (1986) Functional analysis of anterior cruciate ligament instability. Am J Sports Med 14:276–284
20. Vos EJ, Mullender MG, van Ingen Schenau GJ (1990) Electromechanical delay in the vastus lateralis muscle during dynamic isometric contractions. Eur J Appl Physiol 60:467–471
21. Winter DA, Eng JJ, Ishac MG (1995) A review of kinetic parameters in human walking. In: Craik RL, Oatis CA (eds) Gait analysis. Theory and application. Mosby, St. Louis, pp 252–270

Knee Surg, Sports Traumatol, Arthrosc
(2000) 8:270–274

KNEE

DOI 10.1007/s001670000129

Gordian Stutz
Markus S. Kuster
Frank Kleinstück
André Gächter

Arthroscopic management of septic arthritis: stages of infection and results

Received: 28 January 2000
Accepted: 2 June 2000

G. Stutz (✉) · M. S. Kuster · F. Kleinstück
A. Gächter
Department of Orthopedic Surgery,
Kantonsspital St. Gallen,
9007 St. Gallen, Switzerland
e-mail: gordianstutz@yahoo.com
Tel.: +41-71-4941111
Fax: +41-71-4942871

Abstract Seventy-six patients with septic arthritis (78 affected joints) were treated with a combination of arthroscopic irrigation, débridement, and antibiotic therapy according to the tested bacterial sensitivity. There were 62 knee, 10 shoulder, 5 ankle joints, and 1 hip joint. No antibiotics were added to the irrigating solution. The arthroscopic and radiological stage of infection, treatment, and outcome in these patients was analyzed. The patients were classified into three groups according to initial stage of joint infection (stage I: 21 patients, 22 joints; stage II: 43 patients, 44 joints; stage III: 12 patients, 12 joints). Causes of infection were: hematogenous dissemination in 54%, postoperative wound infection in 28% (17% after open, 11% after arthroscopic procedures). Other causes were: 10% intra-articular steroid injections, 3% diagnostic punctures, and 3% open traumatic injury of the joint. In 78% of the infected joints the causative organism could be identified: *Staphylococcus aureus* was the most common organism found (42%), followed by streptococci (15%), pneumococci (6%), *Escherichia coli* (4%), *Staphylococcus epidermidis* (3%), *Borrelia burgdorferi* (3%), and others in 5%. In the stage I group only one patient needed repeated arthroscopic irrigation, in the stage II group 52%, and in the stage III group 75%. Open revision for eradication of the infection was necessary in one joint with stage II and in two joints with stage III infection (3%). Two joints of the stage III group needed additional surgery after successful treatment of the infection. The combination of arthroscopic irrigation and systemic antibiotic therapy was able to cure 91% of the affected joints. Open revision was necessary in 4% of joints. The number of arthroscopic procedures and the efficacy of treatment depended on the initial stage of the infection. It is concluded that an arthroscopic staging of the initial joint infection has prognostic and therapeutic consequences.

Keywords Arthroscopy · Infection · Risk factors

Introduction

The rate of complications and fatal outcomes in the management of septic arthritis was dramatically reduced with the introduction of arthroscopic débridement and the concomitant development of potent antibiotics [37]. The role of continuous irrigation and the use of antibiotic or antiseptic additives are controversial in the literature. Jackson [18] and Jackson and Parsons [19] have proposed a distension-irrigation technique in which one first irrigates and débrides the joint, then inserts two drains into the joint and distends it through the drains with saline solution with antibiotic and mucolytic agents added over 3 h,