

# Knee Joint Kinematics and Kinetics During Walking and Running After Surgical Achilles Tendon Repair

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**Background:** Despite the increasing incidence of Achilles tendon (AT) ruptures, there is a lack of information on the possible risks associated with regular running and walking for exercise after an injury. There are some known kinematic gait changes after an AT rupture, especially at the knee. However, it is not clear whether runners with AT ruptures may be at risk for secondary knee injuries during shod or barefoot running/walking.

**Purpose/Hypothesis:** The purpose of this study was to compare the kinematics and kinetics of barefoot walking and barefoot and shod running between athletes with a history of AT ruptures and a healthy control group. We hypothesized that there would be increased knee joint loads in the affected limb of the AT rupture group, especially during shod running.

**Study Design:** Controlled laboratory study.

**Methods:** Ten patients who had undergone surgical treatment of a unilateral acute AT rupture ( $6.1 \pm 3.7$  years postoperatively) and 10 control participants were matched according to age, sex, physical activity, weight, height, and footfall type. The kinematics and kinetics of barefoot walking and barefoot and shod running were recorded using a high-speed motion capture system synchronized with force platforms.

**Results:** The main outcome measures were lower extremity joint angles and moments during the stance phase of walking and running. After AT repair, athletes had increased internal knee abduction moments during shod and barefoot running compared with the healthy control group ( $P < .05$ ,  $\eta^2 > 0.14$ ). There were no significant differences in kinematics and kinetics during walking between the AT rupture and healthy control groups ( $P \geq .05$ ).

**Conclusion:** After an AT rupture, athletes had increased internal knee abduction moments during running compared with the healthy control group.

**Clinical Relevance:** The increased abduction loads on the knee in patients with an AT rupture could lead to further running-related injuries. However, barefoot walking may be used as a proprioceptive exercise without an increased risk of overuse injuries in these patients.

**Keywords:** proprioceptive exercise; barefoot; shod; gait; internal abduction moment

The incidence of Achilles tendon (AT) ruptures has increased rapidly during the past 3 decades.<sup>23</sup> For most athletes whose sporting activity includes running, jumping, and sudden directional changes, the consequences of this injury are incompatible with maximum sporting performance.<sup>3,29</sup> Nevertheless, surgical and nonsurgical techniques used to treat AT ruptures enable increasing numbers of athletes to return to regular recreational athletic activity.<sup>18</sup> Despite the increasing incidence of AT ruptures in the sporting population, studies investigating movements in

patients who have suffered this injury have focused mainly on walking, while running has (somewhat surprisingly) been neglected.<sup>41</sup> Thus, there is a lack of information on the possible risks associated with the regular use of running after AT ruptures as a form of physical exercise.

During the past 5 years, 3 case studies have been published on shod-running biomechanics in people with AT ruptures.<sup>17,18,36</sup> The first of these case studies indicated that, in running after surgical repair, there may be reduced plantar flexion moments and increased loading on the knee joint of the affected limb.<sup>36</sup> The second case study likewise reported reduced plantar flexion moments in the affected limb but also found considerably higher ground-reaction forces during the loading phase of the affected limb.<sup>18</sup> In

The Orthopaedic Journal of Sports Medicine, 6(6), 2325967118779862  
DOI: 10.1177/2325967118779862  
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both of these studies,<sup>18,36</sup> the athletes' ATs were longer (by 3.5 cm and 4.0 cm, respectively) after surgery. The third case study found a radical change in the footfall pattern of the affected limb (from forefoot to heel contact), thus reducing the loads on the affected AT.<sup>17</sup> A recent study of patients after surgical or nonsurgical treatment of an AT rupture found increased knee joint loads and an insufficient degree of plantar flexor range of motion in affected limbs compared with the contralateral limb during light jogging and hopping.<sup>41</sup>

A major limitation of all the abovementioned studies is their comparison of the affected limb with the contralateral, or unaffected, limb. There is an almost 200 times higher risk of AT ruptures in an athlete's contralateral limb.<sup>4</sup> Additionally, bilateral deficits in ankle joint proprioception, as reported in a study by Bressel et al,<sup>6</sup> suggest that the uninvolved limb may not serve as an effective control. The first running-related AT study with a control group was reported by Jandacka et al.<sup>16</sup> This sagittal plane-only study has been unable to demonstrate overloading of the affected knee as reported by previous researchers.<sup>36,41</sup>

Studies of patients who have suffered an AT rupture have reported reduced proprioception,<sup>6</sup> lower triceps surae muscle volume, increased AT stiffness,<sup>1,6,33</sup> elongated ruptured ATs,<sup>38,40</sup> lower strength in the plantar flexion position,<sup>27</sup> increased muscle activity during locomotion,<sup>38</sup> and more rapid onset of gastrocnemius fatigue.<sup>39</sup> Bressel et al<sup>6</sup> recommended proprioceptive exercises for athletes recovering from an AT rupture. Currently, barefoot running or walking is used as a means of increasing proprioception.<sup>24</sup> Moreover, barefoot running is recommended particularly with regard to reducing knee joint loading.<sup>5,15</sup> However, it is not clear whether runners with AT ruptures may be at risk of a secondary injury during shod or barefoot running.

Therefore, the purpose of this study was to compare the kinematics and kinetics of barefoot walking and barefoot and shod running between athletes with a history of surgically repaired AT ruptures and a healthy control group. Based on previous case studies<sup>17,18,36</sup> and studies on barefoot running,<sup>2,15,37</sup> we hypothesized that there would be increased sagittal and frontal<sup>16</sup> knee joint moments in the affected limb of the AT rupture group, especially during shod running.

## METHODS

### Participants

An a priori sample size estimation was conducted based on a selected key variable (knee internal abduction moment) from a pilot study.<sup>16</sup> A power analysis was performed for

TABLE 1  
Participant Characteristics<sup>a</sup>

	CTRL Group	ATR Group	<i>P</i>
Age, y	33.2 ± 8.0	34.0 ± 8.6	.300
Weight, kg	71.5 ± 12.0	71.4 ± 11.7	.916
Height, cm	173.6 ± 9.1	174.5 ± 10.0	.287
Fat, %	16.5 ± 6.3	18.5 ± 5.6	.344
Body mass index, kg/m <sup>2</sup>	23.6 ± 2.8	23.3 ± 2.4	.508
Difference in Achilles tendon length, mm	2.9 ± 2.4	16.7 ± 9.7	<b>.002</b>
ATRS total score	96.0 ± 6.7	71.1 ± 22.2	<b>.005</b>
Circumference of affected shank, cm	36.4 ± 1.3	35.0 ± 1.9	<b>.010</b>
Circumference of unaffected shank, cm	36.5 ± 1.1	37.0 ± 2.4	.453
Maximum isometric plantar flexion strength, N·m	117.2 ± 26.2	94.2 ± 27.2	<b>.031</b>
FAOS score			
Pain	98.6 ± 2.4	96.7 ± 5.0	.310
Other symptoms	65.4 ± 4.8	63.9 ± 9.6	.702
Activities of daily living	96.9 ± 6.4	98.4 ± 2.5	.538
Sports	93.0 ± 10.1	76.0 ± 12.4	<b>.006</b>
Quality of life	90.6 ± 13.3	78.1 ± 18.9	.125
Silverskiöld test result of affected limb, deg	42.3 ± 8.0	35.8 ± 6.4	<b>.049</b>
Silverskiöld test result of unaffected limb, deg	43.0 ± 7.5	38.6 ± 7.9	.263
Time from surgery, y	—	6.1 ± 3.7	
Sex, male/female, n	7/3	7/3	
Footfall pattern, RFS/NRFS, n			
Shod	6/4	6/4	
Barefoot	0/10	0/10	

<sup>a</sup>Data are reported as mean ± SD unless otherwise specified. Positive and negative values are determined by the right-hand rule. Bolded values indicate significant difference between groups. ATR, Achilles tendon rupture; ATRS, Achilles Tendon Total Rupture Score; CTRL, healthy control; FAOS, Foot and Ankle Outcome Score; NRFS, non-rearfoot striker; RFS, rearfoot striker.

2-way analysis of variance (2 × 2) with a power of 85% and alpha of 0.05. The results of the power analysis determined that a minimum sample size of 18 participants would be required. Therefore, we recruited 20 participants (Table 1). Ten patients who had suffered a noninsertional, unilateral, total acute AT rupture that had been surgically repaired (6 open, 4 mini-open) at least 2 years before the test date served as the experimental group (ATR group). Ten control athletes (CTRL group) without a history of serious lower limb injuries were matched with the experimental group according to age, sex, volume of running, speed of running, weight, height, and footfall type

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One or more of the authors has declared the following potential conflict of interest or source of funding: This research was supported by the grant "Healthy Aging in Industrial Environment" (program 4 HAIE CZ.02.1.01/0.0/0.0/16\_019/0000798).

Ethical approval for this study was obtained from the University of Ostrava.

(rearfoot striker or non-rearfoot striker). Runners who reported current or previous musculoskeletal disorders, neurological disorders, diabetes, or previous surgery (with the exception of AT surgery in the experimental group) were excluded from this study. Approval for this study was obtained from the university's institutional review board. All participants gave their written informed consent before participation in the study.

### Experimental Setup

Reflective markers were attached to the participant, and their positions were recorded in a calibrated laboratory space using a motion capture system consisting of 8 infrared cameras sampling at 240 Hz (Oqus; Qualisys). Walking and running kinetics were recorded using 2 force platforms sampling at 1200 Hz (length, 60 cm) (9286AA and 9281CA; Kistler). The force platforms were positioned in succession on the floor of a 17 m-long running track (9 m from the start of the track). The motion capture cameras were positioned around the force platforms such that at least 2 cameras would capture each reflective marker on the participant at all times. The ground-reaction forces of both lower limbs during 1 running stride were recorded during each trial. Kinematic and kinetic data were temporally and spatially synchronized. Running speed was recorded by 2 photocells. The body composition was determined by a bioelectrical impedance analysis (418 MA; Tanita). The AT length was determined using a sonographic device (Z5; Mindray). The Silverskiöld test<sup>14</sup> was conducted to determine the limitation of a reduced ankle angle in the AT-ruptured limb. Lastly, the Achilles Tendon Total Rupture Score (ATRS)<sup>28</sup> and the Foot and Ankle Outcome Score (FAOS)<sup>32</sup> were completed.

### Protocol

Each participant visited the Human Motion Diagnostic Centre 2 times. During the first visit, the body composition was determined via a bioelectrical impedance analysis, and height and weight were measured. All participants completed the ATRS and the FAOS, subjectively reporting symptoms and function. A physical activity questionnaire was used to determine the participant's current level of physical activity and the level before injury.<sup>11</sup>

A manual goniometer was used for bilateral measurements of active dorsiflexion and plantar flexion with the participant in a recumbent position and the knees in natural extension. The participant then sat with the lower limbs protruding over the edge of the bench. At rest, bilateral dorsiflexion was measured in a position with the knees in active maximum extension and then with the knees relaxed (Silverskiöld test). Lower limb dominance was determined by a test in which the participant kicked a ball at a target.<sup>35</sup> Maximum isometric dorsiflexion and plantar flexion strength were determined bilaterally according to a modified procedure described by Moraux et al.<sup>26</sup> The participant lay on a bench that was adjustable to his or her height to obtain a right angle at the hip, knee, and ankle joints, with

the shank being horizontal. The foot was flat on the dynamometer.

Next, the kinematics and kinetics of walking and running were recorded. Before conducting the measurements, a global coordinate system was created using a right-angle calibration device of known dimensions. Reflective calibration and tracking markers were positioned on the lower limbs and trunk.<sup>17</sup> Before each data collection, a 5-second standing calibration trial of each participant was performed. After removing the calibration markers, the participant was instructed to walk or run along a 17 m-long track. Participants performed in 3 conditions in the following order: (1) walking barefoot, (2) running barefoot, and (3) running shod. Participants had 5 minutes to rest between conditions and 5 trials to adapt to the next condition.

Five valid trials were retained for each condition for subsequent analysis. A valid trial was defined as an attempt in which the walking speed was within the range of  $1.45 \text{ m/s} \pm 5\%$  (approximately the normal walking speed in healthy participants<sup>19,34</sup>) and the running speed was within the range of  $3.2 \text{ m/s} \pm 5\%$ . In addition, in a valid trial, each lower limb had to make full contact with one of the force platforms. In the shod-running condition, participants wore standardized neutral running shoes with a heel-to-toe drop of 12 mm (of 24 mm) (Mizuno Crusader with markers over the shoes). Last, bilateral maximum isometric plantar flexion and dorsiflexion strength were measured.<sup>26</sup>

As part of the second measurement, the length of the AT of each lower limb was measured using a combination of ultrasonography and optoelectronic stereophotogrammetry.<sup>36</sup> The participant lay prone with his or her ankle resting in a relaxed position at the edge of the table. Two markers were positioned on the center of an ultrasound probe held directly over the right and left edges of the sonogram scan area. The ultrasound image was acquired using a diagnostic ultrasound system (Mindray) in B-mode, 10 mHz, with a 75L38EA linear transducer probe. The difference in the positions of the osteotendinous and musculotendinous junctions was identified in the motion analysis system as the AT length. The average from 3 measurements was used for further analysis.<sup>36</sup>

### Data Analysis

The kinematic and kinetic data were processed using QTM (Track Manager; Qualisys) and Visual3D software (C-Motion). Walking and running events were based on the threshold value of 15 N for the vertical ground-reaction force. Ground-reaction force and marker kinematic data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 50 Hz and 12 Hz, respectively. The distal and proximal ends and the local coordinate systems of the lower extremity segments and pelvis were derived from the calibration trial. Ankle, knee, and hip 3-dimensional joint angles were calculated using an  $x$ - $y$ - $z$  Cardan rotation sequence.<sup>12</sup> Angles in the lower limb joints were determined throughout the entire stance phase.

The net internal ankle, knee, and hip joint moments in the sagittal and frontal planes were calculated using a Newton-Euler inverse dynamics technique.<sup>31</sup> All net joint

TABLE 2  
Sagittal- and Frontal-Plane Kinetic Variables<sup>a</sup>

	Barefoot Running		Shod Running		Condition		Group		Condition × Group	
	CTRL Group	ATR Group	CTRL Group	ATR Group	<i>P</i>	$\eta^2$	<i>P</i>	$\eta^2$	<i>P</i>	$\eta^2$
Sagittal plane moments, N·m/kg										
Maximum ankle plantar flexion	-2.90 ± 0.59	-3.06 ± 0.47	-2.65 ± 0.57	-2.74 ± 0.51	<b>.002</b>	0.689	.562	0.039	.381	0.020
Maximum ankle dorsiflexion	-2.83 ± 0.56	-2.90 ± 0.44	-2.56 ± 0.53	-2.49 ± 0.42	<b>.000</b>	0.762	.984	0.000	.222	0.161
Maximum knee extension	1.98 ± 0.65	2.25 ± 0.37	2.33 ± 0.64	2.64 ± 0.66	<b>.001</b>	0.755	.188	0.184	.735	0.013
Maximum hip extension	-2.55 ± 0.82	-2.61 ± 0.51	-2.43 ± 0.88	-2.77 ± 0.61	.869	0.003	.588	0.034	.262	0.137
Frontal plane moments, N·m/kg										
Maximum ankle inversion	0.68 ± 0.34	0.68 ± 0.31	0.59 ± 0.32	0.69 ± 0.25	.521	0.047	.212	0.023	.337	0.103
Maximum knee abduction	-0.65 ± 0.28	-0.85 ± 0.24	-0.74 ± 0.30	-0.92 ± 0.35	<b>.013</b>	0.518	<b>.019</b>	0.477	.791	0.008
Maximum hip abduction	-1.93 ± 0.63	-2.21 ± 0.39	-1.91 ± 0.53	-2.33 ± 0.41	.541	0.043	.123	0.243	.302	0.117

<sup>a</sup>Data are reported as mean ± SD unless otherwise specified. Positive and negative values are determined by the right-hand rule. Bolded values indicate significant difference between conditions across groups as well as significant difference between groups across conditions. ATR, Achilles tendon rupture; CTRL, healthy control.

moments were normalized to weight. Lower extremity joint angles at the instant of initial contact and range of joint motion were determined. In addition, maximum values of sagittal and frontal lower extremity joint moments during the stance phase of walking and running were determined.

### Statistical Analysis

Walking and running were statistically tested separately because of their inherent differences in their locomotor patterns. For walking, a paired *t* test was used to compare the dependent variables of the ATR and CTRL groups. For shod and barefoot running, 2-factor repeated-measures analysis of variance (group: ATR/CTRL; locomotion type: barefoot running/shod running) was used. The injured lower extremity of the ATR group was compared with the matched lower extremity of the CTRL group, and the contralateral lower extremity of the ATR group was compared with the respective lower extremity of the CTRL group. Alpha was set at 0.05 for all statistical analyses.

Partial eta-squared ( $\eta^2$ ) values were calculated as measures of effect size, and values <0.01, 0.01-0.06, 0.07-0.14, and >0.14 were considered to be trivial, small, medium, and large effect sizes, respectively.<sup>8</sup> The analyses were conducted using SPSS Statistics 24 (IBM).

## RESULTS

The ATR group had a significantly smaller circumference of the shank and had lower plantar flexion strength on the affected limb compared with the CTRL group (see Table 1). In addition, the ATR group had significantly greater side-to-side differences in AT length; on average, the AT was 13.8 mm longer on the affected limb of the ATR group versus the CTRL group. There was no maximum isometric dorsiflexion strength difference between the groups on the affected and matched control limbs ( $P \geq .05$ ). Moreover, there was no maximum isometric dorsiflexion and plantar

flexion strength difference between the groups on the unaffected and matched control limbs ( $P \geq .05$ ). The ATR group had lower self-reported outcome scores (ATRS score, 71.1/100 and FAOS Sports score, 76.0/100), indicating that they had some limitation/difficulty with various activities including running. The remaining FAOS scores indicated no altered function in activities of daily living, pain, quality of life, or other symptoms in the ATR group.

For walking, there were no significant interactions or any significant differences in kinematics and kinetics between the ATR and CTRL groups ( $P \geq .05$ ). For running, there were no group × condition interactions for the kinetic and kinematic variables ( $P \geq .05$ ), with the exception of the frontal-plane hip angle at initial contact of the affected limb and the matched control ( $P < .05$ ,  $\eta^2 > 0.14$ ) (Tables 2 and 3). The most notable result to emerge was that there was a significant difference between the ATR and CTRL groups and between conditions (barefoot vs shod) on the affected and matched control limbs for maximum knee abduction moment ( $P < .05$ ,  $\eta^2 > 0.14$ ) (Figure 1 and Table 2). In addition, there was a significant effect of condition for shod running for maximum knee abduction moment ( $P < .05$ ,  $\eta^2 > 0.14$ ). There was also a significant effect of group on the affected limb's knee angle at initial contact during shod and barefoot running ( $P < .05$ ,  $\eta^2 > 0.14$ ) (Table 3). There was no effect of group on the kinematics and kinetics of the unaffected limb compared with the matched control limb during shod and barefoot running ( $P \geq .05$ ).

## DISCUSSION

The aim of this study was to compare the kinematics and kinetics of barefoot walking and barefoot and shod running between patients with a history of AT ruptures and a healthy control group. As we hypothesized, athletes after an AT rupture had increased knee abduction loading during running compared with the control group. Increased knee loading in patients with AT ruptures during light

TABLE 3  
Sagittal- and Frontal-Plane Kinematic Variables<sup>a</sup>

	Barefoot Running		Shod Running		Condition		Group		Condition × Group	
	CTRL Group	ATR Group	CTRL Group	ATR Group	P	η <sup>2</sup>	P	η <sup>2</sup>	P	η <sup>2</sup>
Sagittal plane joint angles, deg										
Ankle at IC	62.43 ± 7.76	64.84 ± 7.10	75.80 ± 15.79	76.76 ± 11.42	<b>.001</b>	0.719	.612	0.030	.714	0.016
Ankle range of motion	32.73 ± 7.46	31.04 ± 7.50	19.15 ± 13.85	17.76 ± 10.65	<b>.001</b>	0.710	.502	0.052	.946	0.001
Knee at IC	-19.88 ± 5.53	-15.50 ± 4.76	-19.62 ± 5.99	-13.98 ± 4.59	.482	0.056	<b>.023</b>	0.452	.482	0.056
Knee range of motion	-32.20 ± 4.95	-35.15 ± 5.29	-35.53 ± 3.93	-39.56 ± 4.95	<b>.011</b>	0.530	.106	0.264	.460	0.062
Hip at IC	48.33 ± 5.14	46.39 ± 7.92	46.75 ± 5.97	46.41 ± 7.14	.188	0.184	.698	0.017	.317	0.111
Frontal plane joint angles, deg										
Ankle at IC	3.28 ± 4.75	4.38 ± 6.49	4.70 ± 5.55	3.26 ± 8.18	.903	0.002	.948	0.000	.356	0.095
Maximum ankle pronation	-10.67 ± 5.04	-9.16 ± 7.53	-9.76 ± 7.12	-11.65 ± 5.91	.257	0.140	.942	0.001	.140	0.225
Knee	5.12 ± 3.51	3.07 ± 3.62	4.22 ± 2.95	2.30 ± 3.38	.115	0.253	.054	0.353	.873	0.003
Maximum knee adduction	6.41 ± 3.41	5.30 ± 4.99	6.18 ± 3.13	4.85 ± 5.47	.547	0.042	.376	0.088	.811	0.007
Maximum knee abduction	-0.97 ± 4.18	-1.57 ± 3.20	-0.58 ± 4.08	-1.74 ± 2.97	.840	0.005	.366	0.092	.292	0.122
Hip at IC	1.10 ± 3.69	3.61 ± 2.51	4.00 ± 2.35	2.97 ± 2.61	.064	0.330	.429	0.071	<b>.026</b>	0.439
Maximum hip adduction	8.61 ± 4.88	9.79 ± 4.43	9.24 ± 4.22	10.68 ± 4.52	.024	0.451	.313	0.112	.821	0.006

<sup>a</sup>Data are reported as mean ± SD unless otherwise specified. Positive and negative values are determined by the right-hand rule. Bolded values indicate significant difference between conditions across groups as well as significant difference between groups across conditions. ATR, Achilles tendon rupture; CTRL, healthy control; IC, initial contact.

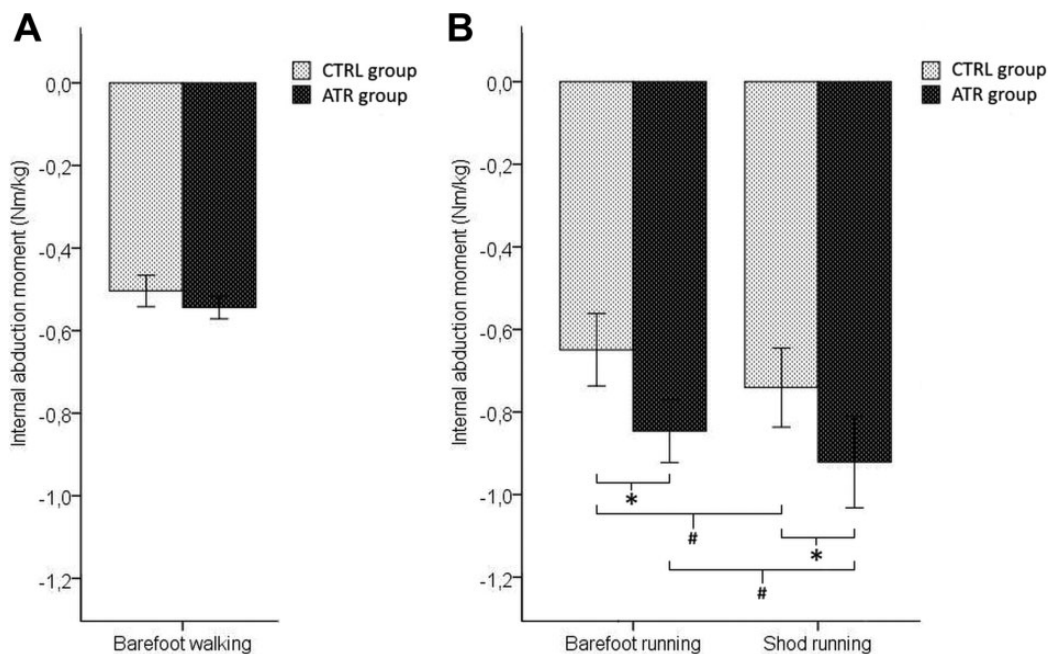


Figure 1. Knee internal abduction moment during stance phase: (A) walking and (B) running. \*Significant difference between Achilles tendon rupture (ATR) and healthy control (CTRL) groups. #Significant difference between shod and barefoot conditions.

jogging has already been suggested by Willy et al.<sup>41</sup> However, they did not use a control group and did not examine the frontal-plane kinematics and kinetics of the knee. Another important finding in this study was that there were no differences in knee loading between the ATR and CTRL groups when walking barefoot. Some authors have suggested that increased knee loads during sports-related activities may place athletes with AT ruptures at a greater

risk for knee injuries that are related to biomechanical overloading, such as medial knee osteoarthritis.<sup>41</sup>

Recently, Kumar et al<sup>21</sup> reported that patients after anterior cruciate ligament (ACL) reconstruction with an increase in medial knee loading show early cartilage degeneration when compared with those who do not have an increase in medial knee loading. In addition, Lynn et al<sup>25</sup> reported that an increased knee abduction moment may

apply abnormal loads to knees with each step. Over time, this altered loading may contribute to the development of medial knee osteoarthritis. The findings of the Kumar et al<sup>21</sup> and Lynn et al<sup>25</sup> studies are consistent with those of Kutzner et al,<sup>22</sup> who showed that knee abduction moment can be used as a surrogate measure of the mediolateral force distribution in the knee joint throughout the stance phase of gait. Thus, it appears that patients who have suffered an AT rupture may have a running-related increased risk of medial knee osteoarthritis. In addition, prospective research of cross-country runners has shown that increased knee internal abduction moment led to a higher risk of some running-related injuries, such as tibial stress reaction, patellofemoral joint pain, or patellar tendinosis.<sup>10</sup>

In the sagittal plane, the knee extension moment in the ATR group increased during shod running compared with barefoot running. In the current study, barefoot running decreased knee frontal-plane loads during the stance phase; however, the ATR group still had a greater knee abduction moment compared with the CTRL group during the barefoot condition. Because of the increases in ankle joint moments (see Table 2) and AT forces in general during barefoot running,<sup>37</sup> we suggest that barefoot running may not be advantageous for athletes with AT ruptures. While it may serve as a protective means against knee injuries and proprioceptive exercise, the greater risk of further AT injuries is problematic. However, as seen in Figure 1A, barefoot walking seems to be a good alternative for proprioceptive exercise without the increased risk of overloading the knee in the frontal plane or sagittal-plane ankle loading.

The results of this study are inconsistent with previous findings that showed reduced plantar flexion moments during walking and light running.<sup>41</sup> Although our results differ from those of some published studies,<sup>7,41</sup> they are consistent with others.<sup>1,16</sup> The cause of inconsistency could be the different physical activity levels of the participants. While Willy et al<sup>41</sup> studied patients with AT ruptures treated operatively and nonoperatively (mean age, 48 ± 10.9 years; mean time after AT rupture, 6.2 ± 2 years; mean FAOS Sports score, 89.1 ± 13.5; mean ATRS total score, 87.0 ± 13.7), in our study, we studied athletes with operatively treated AT ruptures (mean age, 34.0 ± 8.6 years; mean time after AT surgery, 6.1 ± 3.7 years; mean FAOS Sports score, 76.0 ± 12.4; mean ATRS total score, 71.1 ± 22.2).

Proprioceptive exercises are generally recommended for patients recovering from an AT rupture for at least 1 year after surgery.<sup>6</sup> A popular proprioceptive exercise is barefoot running. In a prospective evaluation, it has been suggested that running barefoot may serve as a protective mechanism against knee injuries.<sup>2</sup> Previous experiments have shown some evidence that running barefoot may decrease the knee abduction moment.<sup>5</sup> However, a previous study showed that in an AT rupture group, the plantar flexor muscles appeared to have suffered from a functional deficit even ≥2 years after surgery.<sup>18</sup> The plantar flexors operate primarily in the sagittal plane, and a deficit in the sagittal plane may be substituted by increased loading on the lower limb joints in the frontal plane (see Figure 1).

Another important finding in this study was that the ATR group had increased knee extension at initial contact during

barefoot and shod running. Patients in the ATR group were also shown to have an elongated AT (see Table 1). This finding supports previous research that links AT elongation and a plantar flexor deficit with knee extension.<sup>16</sup> The results of this study suggest that runners with AT ruptures have increased knee extension during shod running, possibly to ensure sufficient tension of the elongated gastrocnemius complex during initial ground contact.<sup>16</sup> As a 2-joint muscle, the gastrocnemius plays an important role as a stabilizer against overextension of the knee and anterior knee laxity.<sup>9</sup> The results of the current study indicate that barefoot running decreased knee extension during initial contact compared with shod running. However, the ATR group still showed increased extension compared with the matched CTRL group. Therefore, a weakened AT could be a major factor causing altered sagittal-plane knee kinematics (extended/locked knee) and consequently increased frontal-plane loading.

Previous biomechanical research is in agreement that a high risk of ACL injuries exists with the presence of a lower knee flexion angle (0°-30°), higher values of frontal-plane knee moments, and higher ground-reaction forces during loading of the lower extremity.<sup>42</sup> A lower knee flexion angle may be a significant risk factor for an ACL injury when landing or when transitioning from running to cutting.<sup>20,30</sup> It appears that an increased knee abduction moment and knee extension across barefoot- and shod-running conditions may predispose patients who have suffered an AT rupture to an ACL injury. However, no data have been reported to show an increased number of ACL ruptures in a population of patients with AT ruptures.

The results of the current study are limited because of its cross-sectional design. Therefore, it is not clear if the biomechanical changes seen are causes or consequences of an AT rupture. A second limitation of the study concerns the locomotor speed of walking and running. The locomotor speeds (1.45 and 3.2 m/s for walking and running, respectively) were relatively slower than would be observed in an athletic competition. An issue that was not addressed in this study was whether there is a difference between shod and barefoot walking. However, it appears that the findings of the current study are consistent with those of Willy et al,<sup>41</sup> who found that shod walking does not overload the knee in patients with AT ruptures when compared with contralateral knee loading. In addition, we did not assess lower limb alignment in the ATR and CTRL groups. It is possible that a varus lower limb alignment could predispose a patient to AT injuries and consequently increased knee abduction moments. Moreover, AT ruptures usually occur during rapid eccentric loading of the plantar flexors.<sup>13</sup> Future studies should investigate limb alignment and explosive actions with participants after an AT rupture, with particular emphasis on the knee mechanics of the affected limb during cutting, stop-and-go, and landing maneuvers.

## CONCLUSION

The results of this study have shown that patients after an AT rupture had higher knee abduction moments and

increased knee extension angles at initial contact during barefoot and shod running compared with healthy controls. In addition, internal knee abduction moments were less with barefoot running. An implication of this is the possibility that patients after an AT rupture have an increased risk of overuse knee injuries during shod and barefoot running. In addition, the results of this study indicate that walking does not impose a load on the knee that is different between those with and without an AT rupture.

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