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Tensile Engagement of the Peri-Ankle Ligaments in Stance Phase

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Abstract

Background—The efficacy of reconstructive surgical procedures that attempt to restore normal ankle kinematics theoretically requires a full biomechanical understanding of the natural human ankle during gait. The contribution of the peri-ankle ligaments versus the articular surfaces to ankle motion control is not yet well understood. Knowledge of the tensile engagement of the peri-ankle ligaments during stance phase is necessary in order to achieve physiologic motion patterns.

Methods—Eleven fresh-frozen cadaver ankles were subjected to a dynamic loading sequence simulating the stance phase of normal level gait. Simultaneously, ligament strain was continuously monitored in the anterior talofibular, calcaneofibular, and posterior talofibular ligaments, as well as in the anterior, middle, and posterior superficial deltoid ligaments. Eight of these specimens underwent further quasi-static range of motion testing, where ligament tension recruitment was assessed at 30° plantar flexion and 30° dorsiflexion.

Results—In the dynamic loading tests, none of the ligaments monitored showed a reproducible strain pattern consistent with playing a role in ankle stabilization. However, in the extended range of motion tests, most ligaments were often taut in plantar flexion or dorsiflexion.

Conclusions—A consistent combination of individual ligament strain patterns that principally control ankle motion was not manifest; rather, none of the ligaments under study were reproducibly recruited to be a primary stabilizing structure. The peri-ankle ligaments are likely to be secondary restraining structures that serve to resist motion, to avoid extreme positions. Stance phase ankle motion appears to be primarily controlled by articular congruity, not by peri-ankle ligament tension.

Clinical Relevance—Reconstructive ankle surgeries which aim to restore normal kinematics should focus on optimizing motion control by means of the articulating surface topography, rather than relying substantially on ligamentous guidance.

Keywords

ankle; ligament; motion control; cadaver experiment

Introduction

Aberrant kinetics and kinematics of the ankle joint, resulting from injury or from disease processes, often trigger a pathomechanical cascade to articular destruction, eventually leading to surgical reconstruction. Attainment of normal biomechanics for ankles with mild to moderate articular degeneration can be pursued through ligamentous reconstruction, corrective osteotomies, or a combination of those procedures.⁸ Severely degenerated cases can undergo

total ankle replacement, an emerging alternative to arthrodesis.²¹ For those reconstructive procedures, improved biomechanical understanding of the natural human ankle during gait is an important key for further development.

Because of the anatomical resemblance of the talo-crural joint to a simple cylindrical or conical bearing, early functional anatomic studies described ankle motion as a single fixed-axis rotation guided only by the contours of the articular surfaces.^{9,12,14} This notion was widely accepted, and in the case of arthroplasty led to several first-generation total ankle replacements employing cylindrical geometry on their articulating surfaces. Ultimately, these hinge-like prosthesis designs resulted in disappointing long-term clinical outcomes.^{3,10} Later, more sophisticated studies of ankle kinematics suggested that the axis of ankle rotation is not fixed, but rather migrates continuously throughout the entire range of motion^{4,14-16,21,23}. The mismatch between implant design and required motion is thought to have led to elevated stresses at the implant/bone or cement/bone interface, resulting in loosening and component failure²¹. Second-generation total ankle replacements were then developed with semi-constrained designs, which share constraint between the implant's articular surfaces and the peri-ankle ligaments. Although some of these designs have demonstrated encouraging intermediate-term results^{1,5,11,19,27,30}, these devices have not fully reproduced the normal kinematics of human ankles^{25,26}.

Ankle motion control is generally considered to be dependent on the complementary roles of the peri-ankle ligaments and the articular surfaces¹⁴, yet the relative contribution of ligaments vs. articular surfaces is not well understood. Although several investigators have studied the effect of ankle position on ligament strain^{7,17,18,20}, tensile behavior during gait has not been thoroughly investigated. We therefore designed this cadaver-based study to explore tensile engagement of the peri-ankle ligaments during simulated stance phase of level gait. It was hypothesized that the peri-ankle ligaments work synergistically, exhibiting a consistent combination of reproducible strain patterns, to help control ankle motion under weight bearing conditions.

Methods

Eleven fresh-frozen human ankle specimens (mean donor age 71, range 57–85) were obtained at autopsy. No deformities, contractures, ligament injuries, or articular degeneration were evidenced by visual or manual inspection. Each specimen was thawed at room temperature before testing and dissected free of soft tissue at the ankle, other than keeping all major supporting ligaments intact. For mounting in the testing fixture, the mid-shaft of the tibia/fibula, the calcaneus, and the distal phalanges were secured in three separate blocks of polymethylmethacrylate.

To monitor peri-ankle ligament condition, miniature differential variable reluctance transducers (MicroMiniature DVRT, Microstrain®, Inc., Williston, Vermont) were attached directly onto the ligaments under study. A device of this type can continuously measure the separation between the two points at which it is sutured, reporting an output voltage which is then converted to length, using a predetermined calibration. The transducers were sutured to the mid-substance of the following six ligaments: the anterior talofibular ligament, the calcaneofibular ligament, the posterior talofibular ligament, and the anterior, middle and posterior bundles of the superficial deltoid ligament complex. The anterior and posterior superficial deltoid ligaments were included for the last nine specimens, since their possible independent behavior was recognized after the first two specimens were tested. The deep deltoid ligaments were not included due to anatomical inaccessibility.

After mounting the strain transducers, each specimen was subjected to a ligament zero-strain determination procedure. The ankle was manually manipulated while visually observing all particular ligaments, to ascertain a point at which each separate ligament became incipiently taut and resisted further motion. Transducer output for that ligament at that point was recorded, and the corresponding transducer length was defined as the zero strain length. This procedure was applied for each of the six peri-ankle ligaments, with reproducibility confirmed by repeated trials. Strain was defined as the percent elongation of transducer length, relative to the zero-strain transducer length for each ligament, so that tautening or slacking of a ligament could be indicated respectively by positive or negative values. These values were utilized only to identify tensile status and to quantify length changes, but not to determine absolute magnitude of strain in individual ligaments.

Experimental loading was applied by a custom fixture (Fig. 1) mounted in a materials testing machine (MTS Inc., Model 858.20, Eden Prairie, Minnesota). This device controlled sagittal kinematics of the ankle (plantar flexion/dorsiflexion) in terms of a user-specified position and rotation rate, while applying axial load. Simultaneously, inversion/eversion, internal/external rotation and anterior/posterior translation were unconstrained, to reproduce natural ankle motion. Each specimen was mounted in the fixture with the ankle in neutral flexion, and one body weight (600N) of axial load was applied and held. The ankle joint was then flexed within the physiologic motion arc during gait, from 15° plantar flexion to 10° dorsiflexion and back again, at a rate of one cycle per second²³. Four flexion cycles were run, with ligament strains continuously monitored and recorded for the last three cycles (Fig. 2). This dynamic loading regime was applied for all of the eleven specimens.

Eight of the specimens were further subjected to an extended range of motion test, to explore ligament strain behavior beyond the motion arc in the dynamic test. For these additional tests, plantar flexion and dorsiflexion were applied quasi-statically under a reduced axial load of 300N (this reduction was to avoid possible ligament damage with excessive flexion.) Strain in each ligament was recorded when ankle position was at 30° plantar flexion and at 30° dorsiflexion.

To describe ligament tension behavior in the dynamic loading test, strain data were utilized to categorize tensile status of the ligaments. Strain greater than +1.0 % were defined as indicating “taut” condition, those less than -1.0 % as indicating “slack” condition. Conditions between those two were designated as “equivocal.” Durations of each condition, as a percentage of the test cycle, were calculated for every ligament in each specimen (Fig. 3). The strain data were further utilized to provisionally indicate approximately isometric length patterns, based on the range of strain values during the motion arc. Data in the extended range of motion tests were utilized to evaluate the effects of both 30° plantar flexion and 30° dorsiflexion on the tensile status of each ligament.

Results

Dynamic Loading Test (Table 1)

The middle superficial deltoid ligament was continuously taut during the motion arc in four of the eleven specimens (#3, 4, 7 and 9), and intermittently taut in another two (#1 and 2) (Fig. 4). In the remaining five, an unequivocally taut condition was never achieved, and the ligament was continuously slack in two of those five. For every other ligament, an intermittently taut condition was attained in less than half of the specimens (anterior talofibular ligament taut in 1/11 specimens, calcaneofibular ligament in 1/11, posterior talofibular ligament in 5/11, anterior deltoid ligament in 4/9, and posterior deltoid ligament in 0/9). Other ligaments were instead continuously slack in some specimens (anterior talofibular ligament in 7/11, calcaneofibular ligament in 4/11, posterior talofibular ligament in 5/11, anterior deltoid

ligament in 5/9, and posterior deltoid ligament in 9/9). No reproducible engagement pattern was demonstrated across specimens for any ligament under study.

As regards the range of strain in the normal motion arc, a nearly isometric length pattern (as evidenced by a 2.0% range or less) occurred frequently; for the anterior talofibular ligament in 5/11 specimens, for the calcaneofibular ligament in 9/11, for the posterior talofibular ligament in 7/11, for the middle deltoid ligament in 7/11, and for the posterior deltoid ligament in 3/9 (Table 1).

Extended Range of Motion Test (Table 2)

At 30° plantar flexion, the anterior talofibular ligament was taut in 3/8 specimens, the calcaneofibular and posterior talofibular ligaments were taut in 2/8, and the anterior deltoid ligament was taut in all eight (Table 2). At 30° dorsiflexion, the calcaneofibular and posterior talofibular ligaments were taut in 6/8, the middle deltoid ligament was taut in 2/8, and the posterior deltoid ligament was taut in 4/8.

Discussion

In this study, function of ligaments in controlling joint motion was explored by means of monitoring the tensile status. A ligament that participates in stabilizing a joint needs to be taut. Slack ligaments cannot provide any force to stabilize the bones to which they attach. Minimally taut ligaments also are likely unable to provide substantial force to stabilize joint motion. Because of the non-linear structural behavior of soft tissues, stiffness in a minimally taut ligament is generally low²⁹, a phenomenon which is well characterized for peri-ankle ligaments.^{6,17,18} In this study, the 1.0% strain threshold was therefore chosen to identify a ligament condition in which the ligament was unambiguously mechanically engaged in stabilizing the ankle, while strain values less than -1.0% were considered to unambiguously indicate that the ligament was not mechanically engaged. Conditions between those two were designated as equivocal, to avoid possible data misinterpretation.

If ankle motion control is principally dependent on the tensile engagement of the peri-ankle ligaments, there should be a more or less consistent combination across specimens of individual ligament strain patterns. For an individual ligament to be engaged in such a combination, the ligament should have a specific strain pattern that depends on ankle position. However, in the dynamic tensile results, no peri-ankle ligament had a specific reproducible strain pattern plausible for stabilizing ankle motion. That is to say, the hypothesized specific combination of peri-ankle ligament strain patterns did not emerge. Furthermore, in every peri-ankle ligament under study, it was common to encounter strain behavior in which the ligament remained slack throughout the experimental motion arc. None of the six tested ligaments was consistently engaged in controlling ankle motion under the experimental weight-bearing condition. Although the experiment did not rule out tensile engagement of the deep deltoid ligaments, the postulated substantial role of the peri-ankle ligaments in controlling ankle motion during stance phase was not supported. Our stance phase simulation did not include the shear and torsional forces that occur during stance phase *in vivo*, though those forces are much less than the axial force and thought to be variable depending on circumstances.²² These quasi-physiologic experimental results argue strongly against an *in vivo* function of the peri-ankle ligaments, although the present protocol admittedly did not replicate the full complexity of *in vivo* kinematics and kinetics.

By contrast, in the extended-range flexion test, all of the peri-ankle ligaments under study, except for the middle deltoid, were often taut at 30° plantar- or dorsiflexion. Those ligaments therefore seem likely to function primarily in restraining extreme flexion of the ankle. Because the calcaneofibular ligament and the middle deltoid ligament cross both the ankle and subtalar

joint, strain in those ligaments is probably also dependent on the position of the subtalar joint. Once external forces induce a displacement or distraction of the ankle, the peri-ankle ligaments will tauten to provide resistance, so that apposition of the articular surfaces can be maintained. The peri-ankle ligaments thus likely are secondary structures that function to restrain the ankle from moving out of the typical positions during stance phase.

In a previous study, Leardini et al.¹³ proposed a two-dimensional four-bar linkage model of the ankle, in which the tibiocalcaneal ligament (which corresponds to the middle deltoid ligament in the present study) and the calcaneofibular ligament were considered as the principal structures controlling ankle motion. That model, however, was based on the result of a cadaver experiment without articular contact loading, under which circumstance the data demonstrated that those two ligaments showed isometric length patterns throughout the entire ankle motion arc. In the present study with articular loading, although both ligaments were often nearly isometric, neither was consistently recruited to be a primary stabilizing structure. As previously demonstrated in other studies^{24,28}, ankle stability under weight bearing conditions is primarily dependent on the ankle articular surface geometry rather than on engagement of the peri-ankle ligaments. That is, ankle motion during stance phase appears to be basically controlled by articular topography rather than by peri-ankle ligament tension.

In conclusion, the experimental results did not support the premise that the peri-ankle ligaments play a substantial role in controlling ankle motion during normal stance phase. Rather, the data suggest they function as secondary restraints, to prevent the ankle from moving grossly out of the normal position. The principal structures that control stance phase ankle motion thus appear to be the articular surfaces, rather than the peri-ankle ligaments. This study casts doubt on the suitability of reliance on ligamentous guidance to restore physiological joint kinematics in ankle reconstruction.

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Fig. 1.

Schematic drawing of the cadaver ankle testing device. It mounts in an MTS Bionix testing machine, which applies axial load and controls flexion angle. Inversion/eversion of the foot is unconstrained, and the axis is aligned to the ankle-subtalar complex to minimize torques associated with axial loading. The axial load platen (not shown) incorporates a linear/rotational bearing that allows free anterior/posterior translation and internal/external rotation of the tibia.

Fig. 2.

Typical transient strain behavior of the peri-ankle ligaments during the dynamic motion arc between 15° plantar flexion and 10° dorsiflexion, in a single specimen (#7). The charts present continuously monitored strain data in: **A**) the lateral ligaments (ATFL - anterior talofibular ligament, CFL - calcaneofibular ligament, PTFL - posterior talofibular ligament), and **B**) the deltoid ligaments (ADL - anterior superficial deltoid ligament, MDL - middle superficial deltoid ligament, PDL - posterior superficial deltoid ligament). Positive values of ankle flexion indicate plantar flexion, while negative values indicate dorsiflexion.

Fig. 3.

An example of the strain behavior analysis for identifying the tensile condition of a ligament in the dynamic loading test. In the upper graph, ligament strain is categorized as taut (strain greater than +1.0 %), equivocal (between plus and minus 1.0%), or slack (less than -1.0%). The duration of each condition is then calculated as a percentage of the motion arc as shown in the lower figure. In this particular case, the bar graph indicates that the taut condition occurred mainly in plantar flexion, and that its duration was 49% of the motion arc.

Fig. 4.

Tensile condition of the peri-ankle ligaments in the dynamic loading test. Bars represent the durations of taut, equivocal, or slack condition in a ligament in each individual specimen. Note that a consistent specific pattern of taut status is not shown in any of the tested ligaments. In most ligaments except the middle deltoid ligament (MDL), continuously slack behavior is common.

Table 1

Range of ligament strain in dynamic loading test (%)

Values indicate the range of strain during the motion arc between 15° plantar flexion and 10° dorsiflexion. Cells shaded gray indicate a range of 2.0% or less, which was provisionally utilized to indicate a nearly isometric length pattern.

Ligament	Specimen										
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
ATFL	1.2	5.2	0.2	0.9	4.2	2.5	3.2	2.0	2.0	4.1	6.2
CFL	0.2	1.0	2.1	1.1	1.0	0.5	1.1	0.2	0.2	2.1	1.1
PTFL	1.7	1.4	2.9	4.1	0.6	0.8	3.2	1.1	1.1	5.8	0.3
ADL	-	-	15.2	5.0	8.2	9.6	7.2	11.8	11.8	12.8	7.7
MDL	9.0	2.7	0.6	0.7	0.6	0.8	0.7	1.2	1.2	8.4	4.8
PDL	-	-	16.4	0.8	4.1	0.1	13.2	5.7	11.5	0.7	3.0

Table 2

Ligament strain in extended range of motion test (%)

Values indicate strain at 30° plantar flexion and at 30° dorsiflexion, by a quasi-static ligament strain measurement, conducted on specimens #4 to #11. Gray-shaded cells indicate a strain greater than +1.0% that indicates the ligament being in taut status.

	Ligaments	Specimen								
		#4	#5	#6	#7	#8	#9	#10	#11	
ATFL	Plantar flexion	-3.7	-2.9	2.3	2.8	3.7	0.7	-0.4	-2.0	
	Dorsiflexion	-6.1	-4.2	-6.6	-5.9	-6.0	-6.3	-8.2	-10.0	
CFL	Plantar flexion	-3.4	-0.8	-2.5	-0.3	-2.8	1.5	3.2	-3.6	
	Dorsiflexion	2.9	2.5	2.7	3.1	2.0	0.5	2.9	-1.8	
PTFL	Plantar flexion	-0.5	0.6	0.3	0.2	-4.0	-4.3	7.2	4.8	
	Dorsiflexion	11.6	4.1	4.0	2.7	4.2	0.7	0.4	3.1	
ADL	Plantar flexion	6.1	3.0	8.3	5.7	9.4	4.6	7.9	4.5	
	Dorsiflexion	-14.0	-5.4	-11.2	-13.3	-4.1	-15.1	-7.7	-9.8	
MDL	Plantar flexion	-0.7	-0.3	0.5	-3.4	-1.5	-2.8	-12.6	-11.1	
	Dorsiflexion	0.1	-1.3	-9.8	-1.8	-3.5	-3.6	1.0	1.7	
PDL	Plantar flexion	-8.1	-11.5	-8.5	-21.0	-27.0	-16.9	-13.5	-15.6	
	Dorsiflexion	2.9	2.2	1.6	6.4	-6.3	0.4	0.5	-3.6	