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Ligamentous Restraints of the Second Tarsometatarsal Joint: A Biomechanical Evaluation

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ABSTRACT

Ligamentous injury of the tarsometatarsal joint complex is an uncommon, but disabling condition that frequently occurs in elite athletes. There are few options for managing these injuries, in part because the relative mechanical contribution of the ligaments of the tarsometatarsal joint is unknown, complicating decisions regarding which ligaments need reconstruction. In the current study, strength and stiffness of the dorsal, plantar, and Lisfranc ligaments of 20 paired cadaver feet were measured and compared. The plantar and Lisfranc ligaments were significantly stiffer and stronger than the dorsal ligament, and the Lisfranc ligament was significantly stronger and stiffer than the plantar ligament.

Key Words: Lisfranc Joint; Ligament; Anatomy; Biomechanics; Cadaver

INTRODUCTION

Low-energy injuries to the tarsometatarsal joint are often sustained during sports and recreational activities, resulting in midfoot sprains.[3,4,6,8,10,19] Unlike high-energy injuries to the midfoot, low-energy midfoot injuries are difficult to manage because of the difficulty of diagnosing the specific structures that have been injured.[1,3,4,6,7,9,15,20] Recent developments in magnetic resonance imaging have improved the specificity to the diagnosis,[11] but the relative mechanical importance of the midfoot ligaments is still poorly understood. If it is not known what mechanical role each ligament plays, it is difficult to determine when reconstruction is indicated, which limits treatment options.

In the current study, the midfoot ligaments of interest were those that maintain the relationship between the base of the second metatarsal and the medial cuneiform because they are the ones most often disrupted in midfoot injuries.

The anatomy of the ligaments of the tarsometatarsal joint is complex. De Palma et al.[5] classified these ligaments into three groups: dorsal, interosseous, and plantar; this classification has been used in the current study. There are three dorsal ligaments attached to the second metatarsal base; one from each of the first three cuneiforms. The current study examined only the dorsal ligament that connects the first cuneiform and second metatarsal and, thus, acts as an aid to the maintenance of the relationship between these rays. The ligaments at the second metatarsal base have a unique arrangement in that there is no intermetatarsal ligament between the first and second metatarsals. Instead, in addition to the dorsal ligaments, there are two ligaments between the medial cuneiform and second metatarsal base. These two large ligaments maintain the relationship of the second metatarsal base to the medial cuneiform. The interosseous ligament, also called the Lisfranc ligament, attaches to the lateral aspect of the medial cuneiform and the medial aspect of the second metatarsal base. The plantar ligament attaches to the lateral aspect of the medial cuneiform and the plantar aspect of the base of the second and third metatarsals. The attachments at the cuneiform end of these two ligaments are very closely related and in the same coronal plane, with the Lisfranc ligament attachment more dorsally situated (Fig. 1).

The relative strength and importance of these three ligaments is not known. Some reports indicate that the dorsal ligaments are weaker than the plantar ligaments

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and that the Lisfranc ligament is stronger than the plantar; however, these conclusions were based on anatomical observations regarding the relative size of the ligaments and not on quantitative measurements.[5,17] The purpose of the current study was to determine the mechanical properties of the dorsal, Lisfranc, and plantar ligaments. Specifically, we tested the hypotheses that: the Lisfranc/plantar ligament complex was stronger and stiffer than the dorsal ligament and that the Lisfranc ligament was stronger and stiffer than the plantar ligament. To our knowledge, the current study is the first report of experimental measurement of the mechanical properties of the dorsal, Lisfranc, and plantar ligament of the second and third metatarsals.

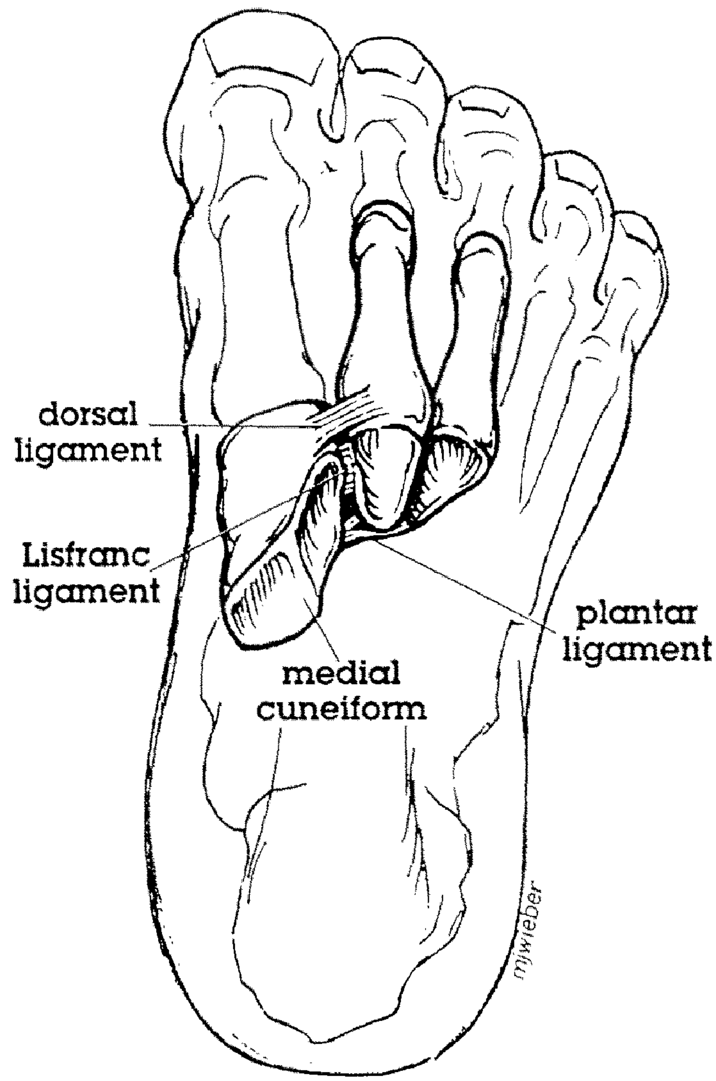

Fig. 1: Anatomical location of the dorsal, Lisfranc, and plantar ligaments.

MATERIALS AND METHODS

Twenty pairs of cadaveric feet were obtained from the State Anatomy Board. All specimens were from elderly individuals, but other demographic details were not available. Before testing, the feet were wrapped in saline-soaked towels and stored in sealed bags at –20°C. Specimens were thoroughly thawed for 24 hours before testing. In each foot, the second and third metatarsals and the first cuneiform were dissected. There was no evidence of previous trauma or arthrosis in any of the specimens. The paired specimens were assigned to one of two test groups (Fig. 2): seven to group I (dorsal ligament) and 13 to group II (plantar/Lisfranc ligament). The specimens in group I underwent two testing procedures. In the initial subgroup, all 14 feet were tested with the dorsal, plantar, and Lisfranc ligaments intact; all other ligaments were excised. Then, in the sectioned subgroup, one of each pair was randomly assigned to undergo sectioning of the dorsal ligament and retesting, and the contralateral specimen underwent sectioning of the plantar and Lisfranc ligaments and retesting. In group II, all specimens underwent dorsal ligament excision and then two testing procedures. In the initial subgroup, the plantar and Lisfranc ligaments remained intact, but all other ligaments were sectioned; all specimens were then tested. In the sectioned subgroup, one of each pair was randomly assigned to undergo sectioning of the plantar ligament and retesting and the contralateral specimen underwent sectioning of the Lisfranc ligament.

The bony portions of each complex were potted in two pieces of polyvinyl chloride pipe using a common epoxy

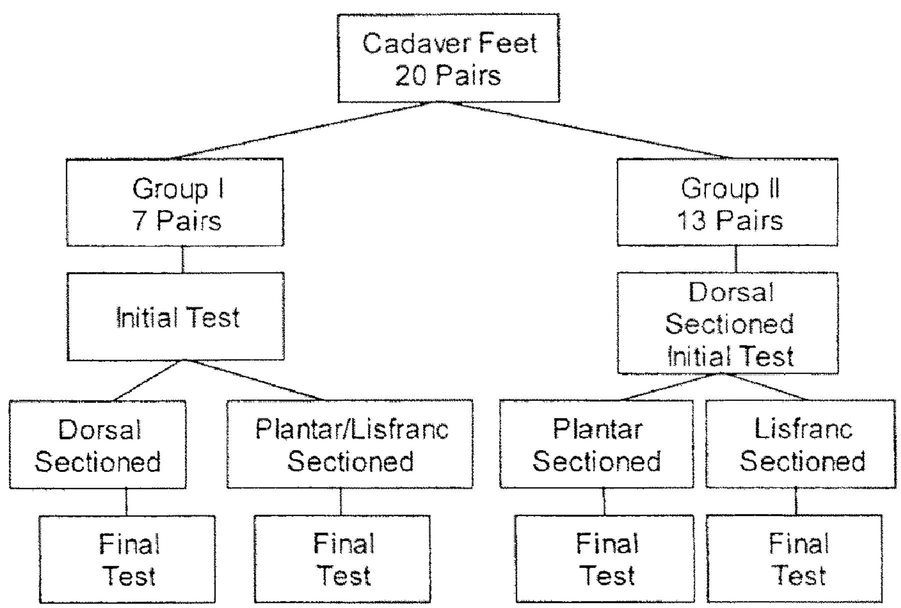

Fig. 2: Assignment of cadaver feet to experimental groups.

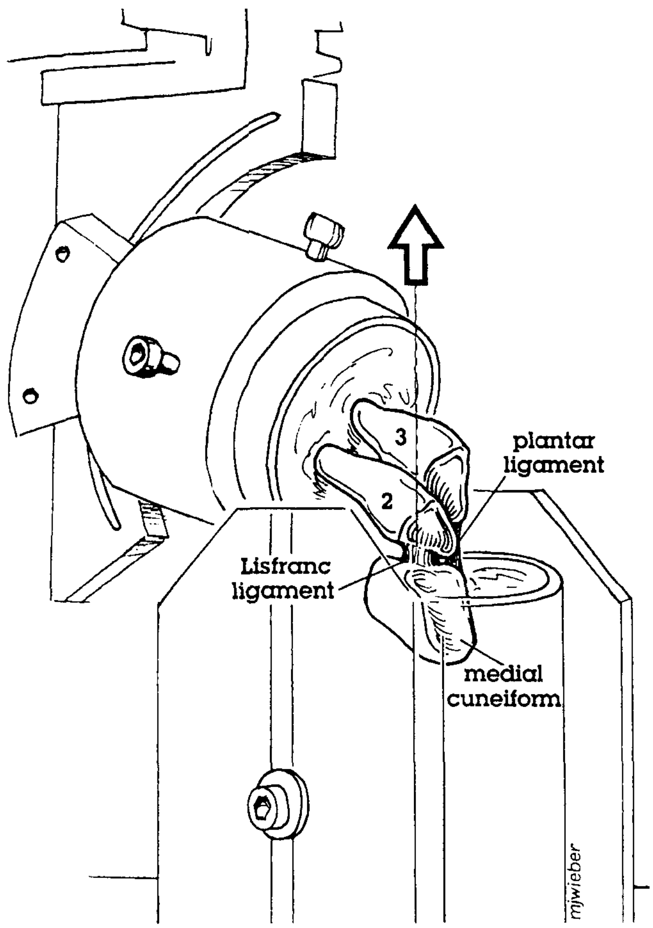

Fig. 3. Intact plantar and Lisfranc ligaments in test apparatus.

resin. The cuneiform was additionally secured by passage of crossed Kirschner wires (K-wires), which had been placed with care before potting to ensure that the wires were not close to the ligamentous attachments. A K-wire was also placed through the heads of the two metatarsals to maintain their near-parallel relationship. Each specimen was mounted on a servohydraulic testing machine (Instron, Canton, MA) so that the applied load was along the longitudinal axis of the ligament fibers (Fig. 3). Specimens were preloaded to 7 N and then elongated at a rate of 0.1 mm/sec until a load of 100 N was reached. Force and deformation data were recorded at 10 Hz, and intact stiffness was calculated as the slope of the force-versus-deformation plot between 50 and 100 N. The specimen was then unloaded and the designated ligament(s) was sectioned. The test was then repeated as before, except elongation was continued until the remaining ligament(s) ruptured. Force and deformation data were recorded and stiffness was measured as before. Strength was defined as the peak load on the force-versus-deformation plot.

The differences in failure strength data between dorsal ligaments and Lisfranc/plantar ligaments (group I) and between Lisfranc and plantar ligaments (group II) were analyzed for significance using paired Student t-tests. A repeated measures ANOVA was used to analyze the effect of condition (initial compared with sectioned) and ligament sectioned (group I, dorsal compared with Lisfranc/plantar; group II, Lisfranc compared with plantar) on stiffness. Post hoc comparisons were conducted using Tukey's test. Unless otherwise specified, results were considered significant at $P < 0.05$.

RESULTS

There was no significant difference in intact stiffness between specimens within pairs within either group, which indicates a homogeneous sample.

In group I, the stiffness (mean ± SEM) of specimens with sectioned dorsal ligaments (115 ± 9 N/mm) was not significantly different than that in initial specimens (104 ± 9 N/mm), whereas specimens with sectioned plantar/Lisfranc ligaments were significantly less stiff (40 ± 9 N/mm) than initial specimens (97 ± 9 N/mm). Specimens tested with the dorsal ligament sectioned were significantly stiffer than those with sectioned plantar/Lisfranc ligaments. Furthermore, the mean strength of the plantar/Lisfranc ligaments (704 ± 93 N) was significantly greater than that of the dorsal ligaments (170 ± 33 N).

In group II, specimens with sectioned plantar ligaments were significantly stiffer (90 ± 3 N/mm) than specimens with sectioned Lisfranc ligaments (62 ± 3 N/mm). There was no significant difference in terms of stiffness between specimens with sectioned plantar ligaments and initial specimens (87 ± 3 N), whereas specimens with sectioned Lisfranc ligaments were significantly less stiff than their corresponding initial specimens (75 ± 3 N). Furthermore, the mean (± SEM) strength of the Lisfranc ligaments (449 ± 58 N) was significantly greater than that of the plantar ligaments (305 ± 38 N).

DISCUSSION

The results of the current study show that the Lisfranc/plantar ligament complex is stiffer and stronger than the dorsal ligament of the second tarsometatarsal joint and that the Lisfranc ligament is stronger and stiffer than the plantar ligament. Saraffian[17] and de Palma et al.[5] noted that the Lisfranc and plantar ligaments are both large and strong, but their assessment of the mechanical properties of these ligaments was based on anatomical observation and not quantitative measurement. Anatomists have disagreed as to which is the strongest.[5,17] To our knowledge, this study is the first report of experimental measurement of the mechanical properties of the dorsal, Lisfranc, and plantar ligament of the second and third metatarsals.

The results of the current study serve as baseline data for choosing a suitable graft material for the reconstruction of the tarsometatarsal joint ligaments. As orthopaedic surgery has advanced, the emphasis on functional reconstruction of injuries has become stronger. Fracture-dislocations of the tarsometatarsal (Lisfranc) joint complex are managed by anatomic reduction and internal fixation. This principle has been extended to the purely ligamentous type of injury seen in athletes.[3] Internal fixation has the disadvantage of allowing no movement at the joint. Secondary osteoarthrosis has been noted at the joint, but whether the injury or the treatment is the cause, is controversial.[16] Abnormally high contact pressures in the tarsometatarsal joint complex, however, have been shown when the first tarsometatarsal joint is included in a reconstructive arthrodesis,[18] and it seems likely that this would also be the case after rigid stabilization of the second tarsometatarsal joint. Before undertaking ligament repair or reconstruction at the base of the second metatarsal, it is important to know the properties of the normal ligaments. This study provides fundamental information needed for development of alternative treatment options, such as reconstruction of the ligaments using a graft to allow preservation of normal joint movement. In the elite athlete, such treatment may be beneficial.

The distinction between Lisfranc and plantar ligaments has not always been clearly made in the past. Several radiographic studies have been published defining the role of magnetic resonance imaging in the diagnosis of ligamentous injury.[11-14] Only one of these defined the Lisfranc and plantar ligaments as separate structures.[11] In that small series (n = 23), Potter et al.[11] reported that injury occurred to both ligaments in three cases, only to the Lisfranc ligament in 12 cases, and only to the plantar ligament in six cases. They considered the plantar ligament and Lisfranc ligament as two bundles of the "Lisfranc ligament," contrary to the descriptions in anatomical studies.[5,11] Another anomaly in the study by Potter et al.[11] was that in cadaveric dissections (n = 5), the plantar ligament was considered to attach to the second metatarsal base and "into tissue between the second and third metatarsals." In the current study, attachment of the ligament was noted to extend to the third metatarsal in all cases, consistent with the findings of de Palma et al.[5]

Interpretation of the results of other studies may also be influenced by clarification of the anatomy. One study investigated changes associated with ligamentous injury and described a useful radiographic sign.[2] Those authors selectively divided the dorsal tarsometatarsal ligaments, the "Lisfranc ligament," and the plantar tarsometatarsal ligaments. The distinction between the Lisfranc and plantar ligament of the second metatarsal base does not appear to have been made. In addition, the methods used to ensure complete division of the Lisfranc ligament only, without inadvertent damage to other structures, are not clearly stated. Shapiro et al.[19] studied ligamentous injuries of the "Lisfranc" ligament, but the published figures show the plantar ligament.

To avoid additional confusion regarding the ligamentous anatomy of the second tarsometatarsal base, we followed the description of de Palma et al.[5] and reserved the term "Lisfranc ligament" strictly for the interosseous ligament attaching the lateral border of the medial cuneiform and the medial aspect of the base of the second metatarsal.

The limitations of the current study are typical of *ex vivo* investigations. The cadaveric specimens used were from an elderly age group, and demographic details were incomplete. Measurements of ultimate load of the ligaments are therefore likely to be underestimates when considering young athletic patients. The specimens were paired, however, and thus the relative strength of the two ligaments is likely to be accurate, because both undergo similar age-related changes.

Although it would have been ideal to isolate the Lisfranc and plantar ligaments with their bony attachments and test them separately to allow direct comparison between both ligaments from the same foot, doing so was precluded by the proximity of the cuneiform insertion of the ligaments. So closely related are the two ligaments that great care was required to ensure accurate selective division. Dividing the cuneiform between the insertion sites of the two ligaments was considered impractical.

Ligamentous injury at the tarsometatarsal (Lisfranc) joint is thought to occur when a tortional force is applied to the axially loaded plantar flexed foot.[3] The testing regimen used in the current study applied distraction at a relatively slow rate. The *in vivo* mechanical environment present during injury is likely more complex than that of the current test protocol. Even so, the purpose of the current study was to determine relative strengths of the various ligaments of the tarsometatarsal joint. The ligaments were elongated along their respective long axes, which is presumably the axis of greatest strength and stiffness. Therefore, even if there are effects of deformation rate and loading conditions on actual mechanical parameters, the relative mechanical parameters should be consistent with the results of the current study, i.e., dorsal ligament weaker than Lisfranc/plantar ligament.

In summary, the current study has shown that the Lisfranc ligament was stronger and stiffer than the plantar ligament of the second tarsometatarsal joint and that the dorsal ligament was significantly weaker than the Lisfranc/plantar complex. These data suggest that injuries with isolated rupture of the dorsal ligament may not be as destabilizing as injuries with ruptured Lisfranc or plantar ligaments and, therefore, that the former may be managed nonoperatively.

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