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The resistance to failure of spring ligament reconstruction

Chandra Pasapula[1], Adam Devany[2], Nicole C. Fischer[3], Coen A. Wijdicks[3], Tim Hübner[3], Franziska Reifenscneider[3], Sajid Shariff[4]

1. The Queen Elizabeth Hospital King's Lynn, King's Lynn, United Kingdom
2. West Suffolk Hospital, Bury St Edmunds, Suffolk, United Kingdom
3. Arthrex GmbH, Munich, Germany
4. Medway Maritime Hospital, Gillingham, United Kingdom

Corresponding Author: Mr Adam Devany, adamdevany@gmail.com

Highlights

- We examined 6 pairs of fresh frozen cadaveric specimens in a standardised and reproducible manner.
- Mean lateral translation measured as surrogate for assessing integrity of repair or reconstruction
- Traditional repair models fail to provide sufficient resistance to planovalgus.
- Using an augmented device such as the internalbrace provides optimal resistance to planovalgus.

ABSTRACT

Introduction:
The spring ligament (SL) is increasingly recognised as the major structure that fails in acquired adult flatfoot deformity (AAFD). This is the first study that demonstrates integrity of repair of the SL.

Patients and Methods:
Six pairs of fresh frozen cadavers were setup in a standardised fashion with ankle in plantargrade (mean age 59 years, BMI 25).
A 25N lateral force was applied to the medial metatarsal head using an algometer. Lateral displacement of the foot was measured with SL intact, sectioned, following FibreWire® repair, then Arthrex InternalBrace (IB) reconstruction, then with selective sectioning of each limb of the IB reconstruction.

Results:
In 12 specimens, overall lateral translation with SL intact was 21mm+-4.9. This increased to 39.2mm+-10.9 ($p<0.05$) with SL sectioning, no significant improvement to 34.2mm+-9.5 with repair ($p=0.159$), before significantly returning to baseline 16.55mm+-5.1 ($p<0.001$) with the IB. Augmenting with FDL did not influence lateral translation ($p = 0.586$).

Conclusion:
Restoration of SL integrity is fundamental to prevent flat foot. Our study shows traditional repair models fail to provide sufficient resistance to planovalgus. Using an augmented device

such as the IB provides optimal resistance to lateral translation and hence planovalgus, particularly the plantar limb of the augmentation.

Keywords: spring ligament, reconstruction, augmentation, pes planus, acquired adult flatfoot deformity, tibialis posterior.

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Introduction

Acquired adult flatfoot deformity (AAFD) is traditionally thought to occur secondary to tibialis posterior (TP) dysfunction. Biomechanical studies have established that functioning of the dynamic supports including the TP tendon, cannot correct the planar deformity and the static ligaments could be of greater importance. An increasing number of specialists believe failure of the spring ligament (SL) as the primary aetiology of longitudinal arch failure, causing a subsequent overload of TP, leading to its gradual deterioration as described initially by 'Johnson and Strom'. [1, 2, 3]

It is uncommon for planovalgus deformity to develop after sacrificing TP for tendon transfer but there have been several described instances of isolated planovalgus foot resulting from proven isolated SL complex injury. We have previously published cadaveric work confirming the SL to be the only structure to induce lateral translation and is the basis of the neutral heel lateral push test in the clinical assessment of SL failure. The presence of SL failure in the absence of a mechanically induced secondary tibialis synovitis has been defined as stage 0 disease. Early reconstitution of the SL integrity at this stage may prevent secondary biomechanical multiligament failure of the foot and prevent TP synovitis. Jennings et al using a 3D kinematic system and a custom frame, demonstrated that the TP tendon cannot biomechanically compensate for failure of the SL and therefore reconstituting this is increasingly recognised as crucial for reconstituting the static restraints to planovalgus collapse of the foot. Hence, restoration of the SL complex is increasingly believed to be a vital part of treating stage one and two disease in the form of a preventative intervention. [4, 5, 6, 7]

To date several techniques have been used to repair or augment the SL, with augmentation gaining popularity more recently. To date no study has demonstrated superiority. Isolated FDL repair and simple repair of the SL has shown poor resistance to failure. Bony augmentation with a lateral lengthening osteotomy has been shown to be more protective but increases risk of iatrogenic complications such as wound breakdown, infection and overload the lateral joints. Modern augmented reconstructions may negate the requirement of this. [8, 9, 10]

A previous study by Palmanovich used a figure of eight type stitch reinforced with a fibre tape into the sustentaculum tali superiorly and inferiorly as a new technique but failed to demonstrate the biomechanical importance of 2 limbs of the repair. [11]

The aim of this is study was to quantify the optimum method of repairing and reconstructing the SL and to determine if augmented reconstruction was better than non-augmented reconstruction, the importance of the individual limbs within the reconstruction using lateral translation of the foot as a measure of integrity of the SL.

Methods and materials:

Preparation and specimens

Six pairs of male fresh frozen cadaveric feet of Caucasian ethnicity were used for the study.

Exclusion criteria included evidence of previous surgery, 1st ray/midfoot deformities, pre-existing tarsometatarsal instability, hallux valgus or a positive lateral push test. Specimens were screened for pre-existing rheumatalogical disease processes that may lead to weakening of the capsuloligamentous structures and excluded.

The Specimens obtained were sectioned through the proximal tibia, retaining proximal attachment of most posterior leg muscles. The integrity of the musculotendinous junction enabled identification and isolation of FDL for transfer and allowing a load through this proximally. Medial sided skin and subcutaneous fat was removed to expose the medial structures over the SL and the TP tendon. This did not affect the mechanical integrity of the foot. The specimen was then mounted on a frame attached to the table using a specialised plate (see figure 1) which was statically locked into the table using bolts. The table's position on the floor was noted to avoid subsequent movement during readings and locked to a static position for stability. The specimens were mounted on to a 2.5cm thick plastic board with multiple pre-existing drill holes to countersink screws. Screws were inserted into the tibia and to the calcaneum posteriorly to give a firm hold to the specimen. The tibial screw was bicortical for maximum purchase and the calcaneal screw was placed 60mm into cancellous bone. This ensured minimum mediolateral movement of the cadavers during readings. The ankle was placed within 20degrees plantargrade and the tibiotalar joint was stabilised with 2mm k-wires.

Specimens and loading measurements procedure

Lateral translation of the talus (Pasapula et al) was used as a guide to the measure of SL integrity. The length of the foot was measured in each specimen to allow standardisation for the size of the foot in relation to the distance from rotation of the talus to the measuring point. [6]

A vertical wire was placed into the hallux to provide a reference point to measure lateral translation. Force was applied using an algometer (MARK-10 Corporation, USA, Series7-50E, range 250N, accuracy ±0,1%) over the metatarsal head to 25N ± 2. The investigator applying the load was blinded from the measurement scale on the frame. Once the 25N force had been applied a photograph was taken for subsequent analysis and measurements of the translations using ImageJ (version 1.45s, NIH, USA). A total of three readings were taken and a mean calculated.

See **figure 1** – Photo of procedure setup applying a lateral force using an algometer

Given that our previous cadaveric study showed that translation greater than 2cm is caused solely by SL sectioning with TP offering no resistance to lateral translation of the foot. TP was excised from the medial foot leaving only a small residual stump on the navicular. The SL was sectioned at mid substance starting at the superior part extending inferiorly and laterally. Dorsal capsule integrity was maintained. This sectioning also exposed the sustanticulum tali allowing for the insertion of the InternalBrace®. [6]

See **figure 2** – Graphical representation of 2 limb InternalBrace reconstruction and FDL transfer

See **figure 3** – Photo of cadaveric 2 limb InternalBrace reconstruction with TP sectioned

Lateral translations were measured in the following scenarios in one foot of each pair of feet: (See **figure 4** – Graphical representation of the scenarios of testing)

1. SL intact: prior to SL sectioning
2. Post SL sectioning and with standard repair pants over vest reconstruction using 2-0 FiberWire® (Arthrex Inc, FL, USA)
3. Post repair, dorsal and plantar SL reconstruction with the InternalBrace® (Arthrex Inc, FL, USA)
4. Post sectioning of the dorsal limb
5. Post sectioning of the plantar limb
6. Post repeat reconstruction of the SL with the internal brace
7. Post sectioning of the plantar limb
8. Post sectioning of the dorsal limb

Lateral translations were measured in the following scenarios in the other foot:

1. SL intact: prior to SL sectioning
2. Post SL sectioning
3. Post standard repair pants over vests using 2-0 FiberWire®
4. Post repair, dorsal and plantar SL reconstruction with the InternalBrace® and FDL-transfer with #2 FiberLoop
5. Post sectioning of the dorsal limb
6. Post sectioning of the plantar limb
7. Post sectioning of the FDL-transfer reconstruction
8. Post repeat reconstruction of the SL with the internal brace
9. Post sectioning of the plantar limb
10. Post sectioning of the dorsal limb

All scenarios were performed in alternating order.

FiberWire® repair was done using two horizontal locked mattress sutures with a pants over vest overlap of the SL. The knots were tied under maximum tension to give the greatest possible overlap of the repair (approximately 5mm).

The InternalBrace® was inserted using a standard technique with the 2.9mm SwiveLock® (Arthrex Inc, FL, USA) placed into the sustanticulum tali (ST) and the 2 strands of the InternalBrace® pulled through a drill hole and a 4.75mm Bio-Tenodesis™ Screw (Arthrex Inc, FL, USA) inserted from plantar to dorsal. The dorsal limb followed by the plantar limb was transected and lateral translations measured.

Subsequently the InternalBrace® was reinserted into the ST or just below if the purchase was not adequate using another 4.75mm Bio-Tenodesis™ Screw to repeat the reconstruction. Subsequently the plantar limb was cut followed by dorsal limb to evaluate which most influenced the strength of reconstruction. Therefore, the inferior and superior limbs were locked into bone with a Bio-Tenodesis™ Screw. Once the two limbs were cut the residual limbs were than reinserted in to the ST or just inferior to then dissect the plantar limb then the dorsal limb.

Specimens were divided into two groups with and without FDL transfer. Lateral translations were measured in the loaded and unloaded model.

FDL was isolated proximally in the calf. Six cadavers underwent an FDL transfer and 6 did not. All scenarios were tested with a 20N load applied proximally to the FDL and without. This allowed us to make a comparative analysis across the specimens as to whether the transfer of FDL added additional value in resistance to lateral translation and hence further augment the repair.

Statistical analysis and modelling

All measurements were adjusted based on a scale factor to consider the size of the foot. We judged that the centre of rotation of the foot was around the talonavicular joint and the larger the foot the greater the overall translation of the foot would be amplified, despite the same degree of motion around the talonavicular joint.

Primary outcome measurements:

Statistical analysis was undertaken with SPSS (SigmaPlot, v13.0, Systat Software, Inc, USA) using one Way ANOVA Analysis (table 1) for comparision of all tests and paired t-test (table 2) for pair comparison with a significance level of 0.05. Primary outcome measure was lateral translation of the foot to serve as a guide to SL integrity.

Results:

Figure 1 shows the main results of lateral translation for all scenarios described above, normalised to a mean foot length of 25.3cm. Tables 1 and 2 show statistical significance for all scenarios modelled.

Lateral translation of the intact group is 22.1mm ± 4.9mm for loaded FDL and 20.6mm± 2.8 (p=0.953) for unloaded FDL. With SL sectioning showing a significant difference from 21.4mm±4.1 to 39.2mm±10.9 (p<0.001).

A standard ligament repair exhibits no statistical significant difference compared to the sectioned stage, 34.2mm±9.5 to 39.2mm±10.9 (p=0.472). Following primary (16.6mm±5.1) and secondary (21.2mm±6.8) repairs with InternalBrace® there is no significant difference to the intact scenario (21.4mm±4.1), p=0.531 and p=0.953. There was no difference between the InternalBrace® reparation with or without FDL-transfer (p=0.174 and p=0.329). Subsequently dividing the dorsal and the plantar limb of the first repair and in a changed order of the second repair, the dissection of the plantar limb show both times a significant difference to the intact and with InternalBrace® repaired scenario (p<0.001 between all scenarios). In an extra stage the FDL-transfer was cut as well without any statistical difference compared to the cut of both limbs of the InternalBrace® (p=1.000).

Figure 5 Whisker box plots showing lateral translation for all tested groups.

Discussion

The role of the SL and its mechanical contribution to the medial longitudinal arch and AAFD has long been debated. [2, 12]

In 2003 only 50% of surgeons believed that addressing this important structure was surgically important. Many specialists now believe that the primary cause of planovalgus is failure of the SL, leading to subsequent failure of the other ligaments causing a secondary overload of TP. The absence of TP synovitis in the presence of a failed SL has been introduced as stage zero disease and can be tested for in isolation using the neutral heel lateral push test. Pasapula showed that significant lateral translation of the foot was only influenced by SL sectioning regardless of the function of TP and hence the basis of the test. Saxby showed cases of proven SL failure without TP synovitis with a planovalgus foot. [4, 6]
Earlier diagnosis by utilising the neutral heel lateral push test offers the prospect of intervention at an earlier stage in the natural history of the condition, reducing the need for more complex procedures. [13]

Jennings used a 3D kinematic system with a custom-loaded frame in the invitro model to quantify rotation about the talus, navicular, and calcaneus in 5 specimens before and after sectioning the SL complex, while incrementally tensioning TP. Sectioning the SL complex produced significant changes in talar, navicular, and calcaneal rotations. More importantly they demonstrated that sectioning the SL complex created instability in the foot for which TP was unable to subsequently compensate. They concluded that the SL was the major stabiliser of the arch during midstance and that TP is incapable of fully accommodating for its insufficiency, suggesting that the SL complex should be evaluated and, if indicated, repaired in flatfoot reconstruction. [7]

To our knowledge there have been very few studies demonstrating the biomechanical resistance to different types of repair models and no studies which tests this in isolation without the use of osteotomies. Previous studies have shown that a simple pants over vest repair provides very little resistance to failure of the repaired SL. Previous attempts at further reinforcing the SL strength to failure relied on the use of osteotomies such as lateral column lengthening which adds to the overall resistance to failure without increasing the inherent strength of the ligament reconstruction itself. This serves as a confounding variable when attempting to assess the integrity of SL reconstruction. Dorsal and plantar limbs have been used in the reconstructions and it is unknown if both contribute to the stability of the arch. [8, 9, 10, 11]

Our study demonstrates as have previous studies, that a simple repair shows statistically significant lack of resistance to lateral translation compared to the intact SL. $p>0.05$ despite using 2-3 locked horizontal mattress sutured to obtain optimal purchase of the tissue. Furthermore, performing a 5mm overlap repair is technically easier in the cadaveric model compared with in vivo and still unable to stabilise the talonavicular joint. We accept in all scenarios there would be healing and the in-vivo model would not rely solely on the intrinsic strength of the suture material alone over a 6-week period. We also accept that the FDL tendon would naturally integrate and may provide additional resistance to failure.

This model of reconstruction using the Arthrex InternalBrace® is biomechanically advantaged as functions independently from the attenuated native structures. The inherent material strength offers large resistance to failure compared to traditional suture materials, with high pull out strength. We demonstrated that the SL reconstruction model using the Arthrex InternalBrace® was at least as strong as the intact SL $p<0.001$. We predict that integration of the limbs into the bone and additional collagen formation along the ligament repair would probably add additional strength to the repair.

It is unknown whether the dorsal limb adds resistance in the axially loaded foot but may have a role in resisting plantar and complex rotary forces. We accept that this was not tested. We showed that there was little additional benefit to lateral translation in the use of the dorsal limb and therefore probably adds very little additional benefit. It does however enable the process of tying off the InternalBrace®, particularly in the scenario of poor bone quality where purchase of the Bio-Tenodesis™ Screw may be difficult. Overall, we believe that the optimum method of fixation is therefore a two-plantar limb construct.

Despite proving validity of using lateral translation as a measure of SL integrity in our previous paper, there are of course limitations. In the laboratory setting the lateral translation due to SL failure is easier to measure using a reproducible, standardised setup. During physiological loading the load would be much greater, in multiple planes and through repeated cycles, particularly the vertical plane, not directly tested in our static model. This could only be reproduced using a dynamic gait simulator. Nevertheless, lateral applied load showed statistically significant differences, making it suitable for clinical examination and comparison of displacement. [6]

There may be a role in stage zero and one tibialis dysfunction syndrome to reconstruct the SL and prevent secondary tibialis synovitis and prevent secondary TMT instability. Earlier reconstruction may prevent subsequent massive biomechanical failure of the foot or stage two disease which we commonly see. This may also serve as a guide in treating patients which have pes cavus with SL failure. [6]

The position of the SL complex is both medial and plantar, therefore its position and location around the talonavicular axis will resist both valgus and planus loads. The valgus component of the arc of rotation at the talonevicular joint is easier to visualise clinically and is the basis of the neutral heel lateral push test. [14]

We do not believe that the FDL adds a biomechanical advantage but do believe that a secondary TP synovitis may render the tendon ineffective biomechanically and therefore still support the use of transfer to augment TP in stance. In the absence of the SL the talus head would still be allowed to sublux medially and exert pressure over the tendon and cause a subsequent mechanical attrition (third pulley affect). We applied a 20 N force though the tendon in our model to see if this would add additional resistance to lateral translation of the foot. There was no statistically significant difference in the loaded and unloaded group. We also acknowledge several issues are present in the FDL tendon transfer including optimum tensioning, the change in excursion distance and the FDL amplitude is less in the non-cadaver model. We accept in the non-cadaver model the tendon would be more integrated into the bone and the loads going through may be greater and therefore provide more functional augmentation to the SL. We believe its use as a substitute for the SL is not justified however its use as a substitute for the diseased TP tendon post resection or to augment may be worthwhile. It may be more prudent to preserve the original musculotendinous unit and more specifically address the SL. We accept the augmentation of the SL does not negate the use of osteotomies. However, in stage zero and one dysfunction bony procedures may not be required. In stage two however, it is clear there are multiple biomechanical failures that need to be addressed including medial column instability and tight gastrocnemius and fixed supination deformity. This can only be achieved with osteotomies and arthrodeses. [6]

We accept that limitations exist in this static model. Repetitive cyclical loading, endurance limits and maximum load to failure were not tested.

Conclusion:

Early reconstruction in AAFD may prevent progression to stage two dysfunction. We believe that once native structures have failed, repairing the ligament alone offers little resistance to pes planus. Therefore, the optimum recommended treatment is by an augmented device using the InternalBrace® in the two-limb construct.

Results from our biomechanical study show FDL tendon transfer adds little biomechanical strength to the SL repair construct. Our results also show that the dorsal limb of the InternalBrace® SL reconstruction construct adds little resistance to lateral translation forces, with most of the resistance coming from the plantar limb. Further work needs to be done to see whether a two-plantar limb construct is therefore biomechanically better than a combined dorsal/plantar limb Internal Brace construct.

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figure 1

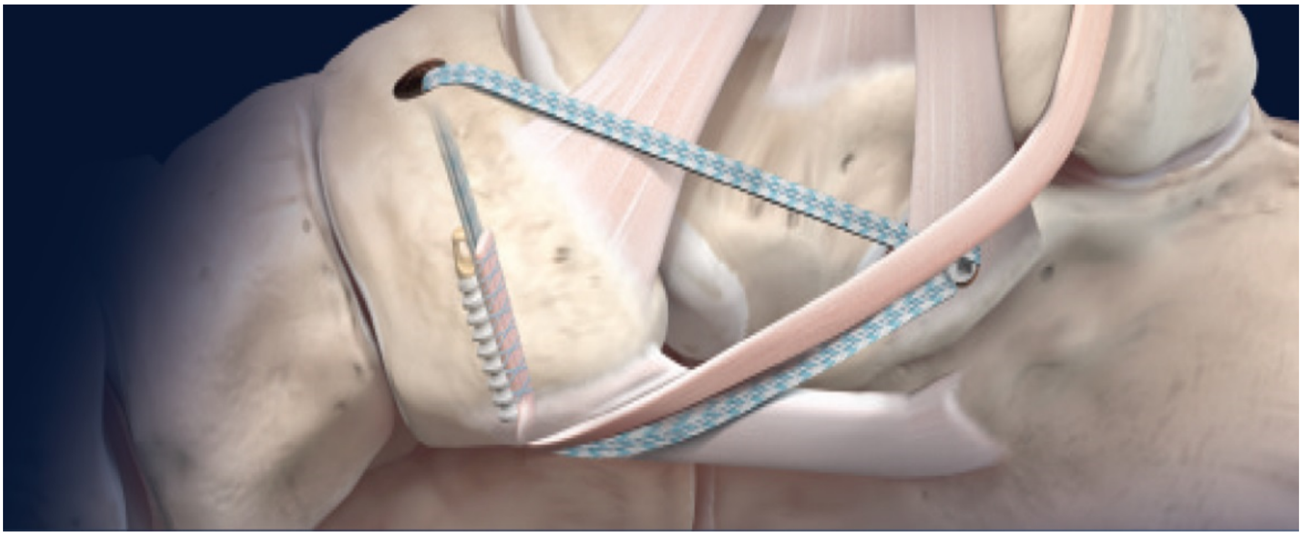

figure 2 –

figure 3 –

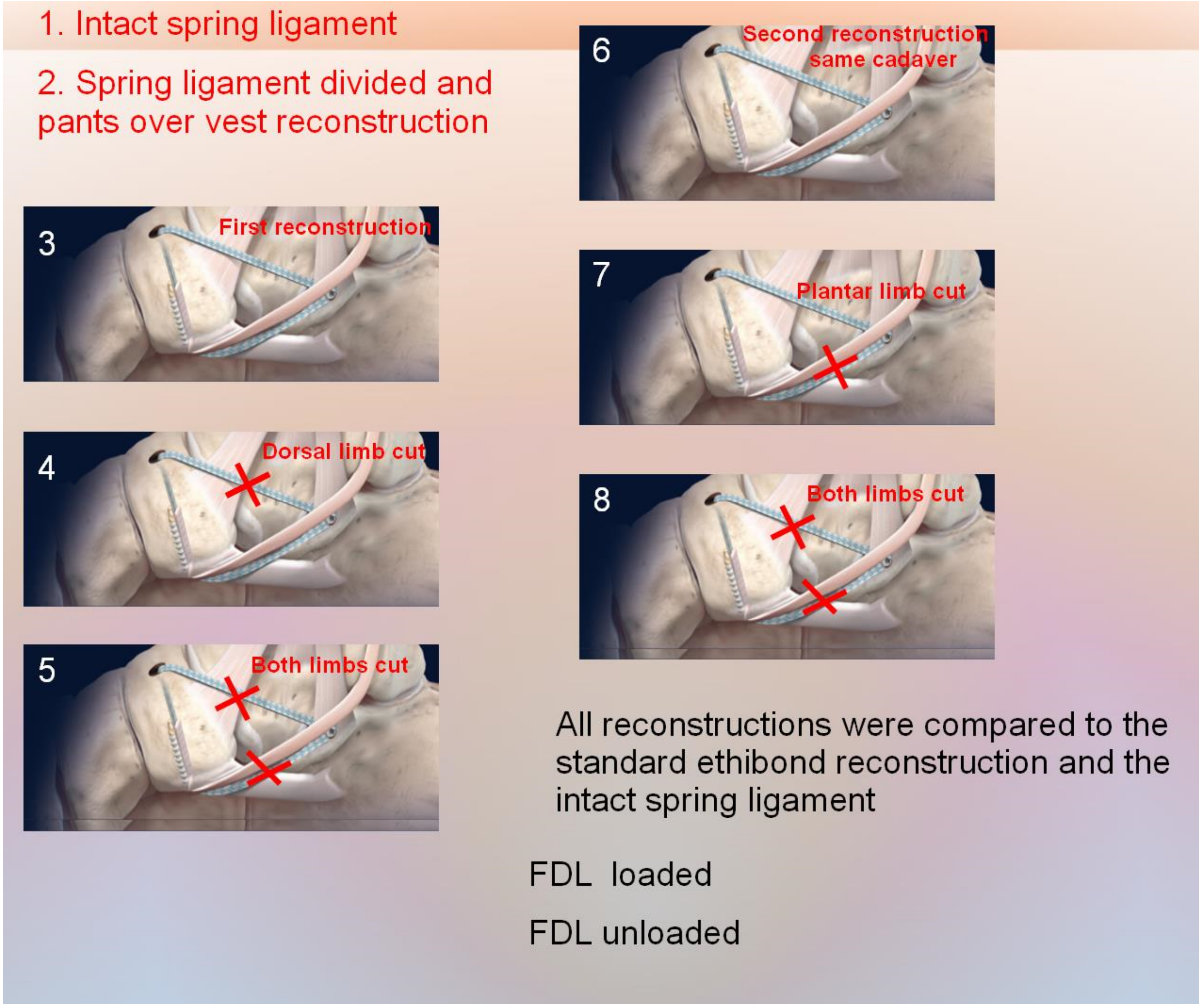

figure 4 –

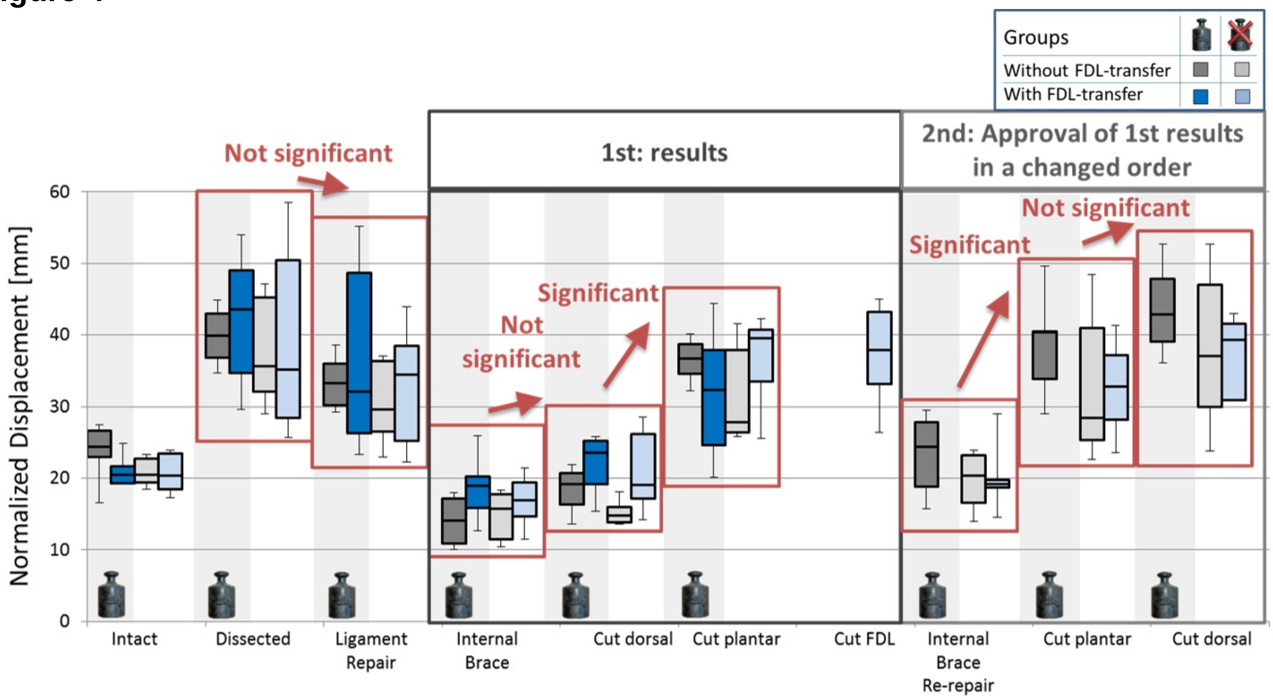

Figure 5

Table 1: One Way ANOVA Analysis of all scenarios (grey marked with p-values <0.05). Each scenario represents all data from with/without FDL transfer and loaded/unloaded.

	Intact	**Dissected**	**FiberWire**	**1st IB w/wo FDL**	**1st Cut dorsal**	**1st Cut plantar**	**2nd IB w/wo FDL**	**2nd Cut plantar**	**2nd Cut dorsal**
Intact	-	<0,001*	<0,001*	0,531*	0,980*	<0,001*	0,953*	<0,001*	<0,001*
Dissected		-	0,472*	<0,001*	<0,001*	0,764*	<0,001*	0,764*	0,992*
FiberWire			-	<0,001*	<0,001*	0,997*	<0,001*	0,997*	0,736*
1st IB w/wo FDL				-	0,884*	<0,001*	0,746*	<0,001*	<0,001*
1st Cut dorsal					-	<0,001*	0,988*	<0,001*	<0,001*
1st Cut plantar						-	<0,001*	0,998*	0,927*
2nd IB w/wo FDL							-	<0,001*	<0,001*
2nd Cut plantar								-	0,906*

*only four out of five pairs

Table 2: Paired t-test overall scenarios, grey marked with p-values <0.05.
*only four out of five pairs, **only three out of five pairs

	Intact	Dissected	Fiber Wire	1st IB	1st Cut dorsal	1st Cut plantar	2nd IB	2nd Cut plantar	2nd Cut dorsal
Loaded vs unloaded Without FDL	0,056*	0,731*	0,259*	0,680*	0,027*	0,272*	0,118**	0,114*	0,822**
Loaded vs unloaded With FDL	0,557	0,387	0,276	0,285	0,590	0,392*	NA	NA	NA
With vs without FDL Loaded	0,608	0,648	0,550	0,174	0,058	0,388	NA	NA	NA
With vs without FDL Unloaded	0,811*	0,260*	0,273*	0,329*	0,104*	0,267**	0,785**	0,849*	0,776**