

# Biomechanical comparison of tenodesis reconstruction for subtalar instability: a finite element analysis

Can Xu

Central South University Xiangya hospital

Mingqing Li

Xiangya Hospital Central South University

Chenggong Wang

Xiangya Hospital Central South University

Hua Liu (✉ [liuhua345@163.com](mailto:liuhua345@163.com))

Central South University, Xiangya hospital

---

## Research article

**Keywords:** finite element, subtalar instability, tenodesis reconstruction, biomechanical, kinematic characteristics

**Posted Date:** February 10th, 2020

**DOI:** <https://doi.org/10.21203/rs.2.22988/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

---

# Abstract

**Background:** There are several types of tenodesis reconstruction designed for subtalar instability. However, no comprehensive comparison has been conducted among these procedures in terms of their correcting power so far. The objective of this study is to evaluate the biomechanical behaviors of 5 representative procedures through finite element analysis.

**Methods:** A finite element model was established and validated based on one of our previous studies. The Pisani interosseous talocalcaneal ligament(ITCL) reconstruction, Schon cervical ligament(CL) reconstruction and Choisine calcaneofibular ligament(CFL)reconstruction were compared on a model with the CFL, ITCL and CL sectioned. The Schon triligamentous reconstruction and Mann triligamentous reconstruction were compared on a model with the CFL, ITCL and CL, as well as the anterior talofibular ligament (ATFL) sectioned. The inversion and external/internal rotation were quantified in different ankle positions with rotational moment.

**Results:** For single ligament reconstruction, the Choisine CFL reconstruction provided the greatest degree of correction for subtalar instability, followed by the Schon CL reconstruction and then the Pisani ITCL reconstruction. For triligamentous reconstruction, the Mann procedure outperformed the Schon procedure in alleviating the subtalar instability.

**Conclusion:** The finite element analysis showed that the Choisine CFL reconstruction and Mann triligamentous reconstruction provided the greatest degree of immediate postoperative subtalar stability. However, both procedures could not restore the biomechanical behaviors of the subtalar joint to normal. The long-term efficacy of these procedures warrants further investigation using a substantially larger sample of clinical cases.

## Background

Subtalar instability is a common functional talocalcaneal instability always coupled with lateral ankle instability. It was reported that about 10–25% of patients with lateral ankle instability suffered from subtalar instability[1, 2]. Subtalar instability mainly results in varus tilt and anterior translation of the calcaneus. However, its clinical manifestation is often covered by the lateral ankle instability, for which, it is only recognized as a separate clinical condition that needs specific treatment in recent years[3].

The exact aetiology of subtalar instability is still unknown. Several cadaveric studies reported that the main ligaments which stabilize the subtalar joint were the calcaneofibular ligament(CFL), the interosseous talocalcaneal ligament(ITCL) and the cervical ligament(CL) [4–7]. For chronic subtalar instability, conservative therapies such as proprioceptive training, stretching of the Achilles tendon, and prescription of orthosis are the primary treatment. When these conservative treatments fail, surgery is indicated. The earlier operation adopted for subtalar instability was duplicated from the procedures for stabilizing the lateral ankle. Most of them, such as the Elmslie[8], Chrisman-Snook[9] and Watson-Jones[10] procedures, attempt to recreate the CFL and anterior talofibular ligament (ATFL). Theoretically,

CFL recreation is effective in stabilizing the subtalar joint because the CFL can bridge the posterior facet of the subtalar joint. However, the ITLC and CL, which play an important role in subtalar instability, were not recreated in these approaches.

Therefore, new procedures including the Pisani ITCL reconstruction[11], Schon CL reconstruction[12], Choisine CFL reconstruction[13], Schon triligamentous reconstruction[12]and Mann triligamentous reconstruction[14] were developed.

Any procedures for joint stabilization should be evaluated for biomechanical effectiveness. The goal of these tenodesis reconstructions is generally to mimic the functions of ligaments as far as possible. To the best of our knowledge, for these newly developed tenodesis procedures, only their clinical outcomes were reported, while their effects in stabilizing the subtalar joint have not been compared before. Therefore, which one is the best procedure remains unknown.

Some cadaver studies have evaluated the effects of different ligaments in stabilizing the subtalar joint. However, to compare these different types of tenodesis reconstruction, the cadavers to be tested should be strictly the same in terms of their material properties and morphologies, in order to ensure the comparability of the experimental results. This is difficult to achieve under the current laboratory setting. The finite element analysis(FEA) is a reliable tool for the quantitative evaluation of biomechanical performance. By using FEA, one model can be tested on the basis of the same material properties and morphologies under several different loading settings. Moreover, FEA can also derive a number of invaluable outputs such as the contact pressure and internal stress, and therefore, it is useful for preoperative planning and surgery assessment. Referencing to a previous study[15], an FE model of the foot and ankle containing 28 bones (tibia, fibula and 26 foot bones), sesamoids, plantar fascia, 24 main ligaments, and cartilage was developed and used to compare 5 different tenodesis reconstructions over their biomechanical behaviors. The goal of this study is to provide reference for the optimal design of subtalar stabilization.

## Methods

An FE model of subtalar instability was developed based on one of our previous studies[15]. The subtalar instability was simulated by removing the CFL, ITCL and CL, as suggested by a previous cadaveric study[13]. Due to the fact that subtalar instability rarely occurs alone, the ATFL was also removed before performing the analysis of Schon triligamentous reconstruction and Mann triligamentous reconstruction.

### Model development

First, computerized tomography(CT) scans of the foot and ankle at 0.5 mm intervals of a healthy male adult volunteer(30 years old with a height of 170cm and a weight of 68 kg)were used to develop bony structures. The DICOM formation data of the CT images was imported to MIMICS 17.0(Materialise, Belgium) for processing. These images were then segmented in order to identify the boundaries of the bones. Then, the STL data of each bone was imported to Geomagic studio 12.0(Geomagic Inc., Research

Triangle Park, NC), and the point clouds data was transferred to a non-uniform rational B-spline(NURBS) curve model with a smooth bone surface in Geomagic studio. Finally, all the geometric models of the bony structures were imported to Hypermesh 13.0 to generate the FE model. The bony structures were meshed with rigid surface elements in view of their small strain compared to soft structures.

Subsequently, the magnetic resonance imaging (MRI) scans were used to develop the soft tissue geometry, including ligaments and cartilage. Ligaments were added manually into the 3D models. The insertion and the original site were identified by MRI presentations while referencing to previous journal papers and textbooks[16, 17]. Then, the ligaments of hindfoot and midfoot(24 ligaments) were added into the model, but the forefoot ligaments were simplified for they might not contribute to hindfoot stability. The cartilages of tibiotalar, subtalar, talonavicular and calcaneocuboid joints were identified on T1-weight MRI images. Then, their geometries were generated in MIMICS and modified in Geomagic studio. Finally, these cartilages were incorporated to the joints and meshed in Hypermesh. The final FE model consisted of 178370 elements and 69517 nodes(Figure.1). The simulation was performed in ABAQUS 6.13(SIMULIA Inc., US).

The ligaments of the tibia and fibula were assigned with non-linear force-displacement equations[18]. The material properties were expressed as curve fit data (a and b) for an elastic force-strain response function( $T(\epsilon)=a(e^{b\epsilon}-1)$ ). The tibionavicular ligament was assigned with a linear stiffness k, which was provided[19](Table 1).The mechanical properties of the hindfoot and midfoot ligaments were assumed to be equal to the ATFL and scaled by their relative cross-sectional areas. The ATFL had a cross-sectional area of  $62.85\text{mm}^2$ [19], and the areas for other ligaments were provided by Mkandawire[20] and Shin[21] (Table 2). The linear elastic stiffness values of the long/short plantar ligaments and plantar fascia were given by literature[22, 23](Table 3).

Table 1.Properties of tibia, fibula and hindfoot ligaments[18, 19].

Ligament	a(N)	b
Anterior talofibular	7.18	12.50
Anterior tibiofibular	5.52	22.63
Anterior tibiotalar	2.06	20.11
Calcaneofibular	0.20	49.63
Posterior talofibular	0.14	44.35
Posterior tibiofibular	6.87	20.07
Posterior tibiotalar	1.34	28.65
Tibiocalcaneal	0.51	45.99
Tibionavicular	k=39.1 N/mm	

Table 2.Properties of hindfoot and midfoot bone ligaments[20, 21].

Ligament	Area (mm <sup>2</sup> )	Area ratio
Anterior talocalcaneal	14.4	0.229
Posterior talocalcaneal	14.96	0.238
Lateral talocalcaneal	6.84	0.109
Medial talocalcaneal	14.91	0.237
Interosseous talocalcaneal	72.80	1.158
Dorsal talonavicular	35.15	0.559
Interosseous calcaneocuboid	72.80	1.158
Plantar calcaneocuboid	98.70	1.570
Inferior calcaneonavicular	9.23	0.147
Superomedial calcaneonavicular	161.00	2.560
Dorsal cuboideonavicular	13.10	0.208
Plantar cuboideonavicular	27.80	0.442
Interosseous cuboideonavicular	14.01	0.223

Table 3.Properties of plantar fascia and long/short plantar ligaments[22, 23].

Ligament	Stiffness k (N/mm)
Plantar fascia	203.3
Long/Short plantar ligament	75.9

The cartilage was defined as being neo-Hookean hyperelastic with  $E=10\text{Mpa}$  and  $\nu = 0.45$ [24]. The contact of joints was simulated by adding a surface-to-surface contact element between the cartilage of joints, with a coefficient of friction( $\mu$ ) of 0. The peroneus brevis tendon used as graft was also considered as a linear elastic material with an elastic modulus value of  $E = 149.7 \text{ MPa}$  and a cross sectional area of  $19.5\text{mm}^2$ [25]. The hamstring tendon used as graft was assumed as isotropic hyperelastic; its strain energy density function was obtained from a previous paper[26].

### Simulation of subtalar instability and validation

In previous cadaveric studies, the subtalar instability was usually simulated by sectioning the CFL, CL and ITCL[4, 13]. This method was also adopted in our numerical analysis. The model was validated by comparing the results of our numerical analysis with previous experimental data[4, 13]. It was found that the inversion and external rotation of the subtalar joint in the intact/instability model under a torsional moment of 4 Nm were consistent between our simulation and Pellegrini's experiment(Table 4). The inversion under 1.5Nm and the internal rotation under 3Nm of the subtalar joint in our simulation were close to Choisne's results(Table 5).

Table 4. Comparison of inversion(4Nm) and external rotation(4Nm) between our simulation and Pellegrini's experiment[4].

		Cadaveric model	FE model
Intact	Inversion	7.2	7.0
	External rotation	4.8	4.8
Subtalar instability	Inversion	12.8	12.7
	External rotation	8.0	7.5

Table 5. Comparison of inversion(1.5Nm) and internal rotation(3Nm) between our simulation and Choisne's experiment[13].

		Cadaveric model	FE model
Intact	Inversion	7.0	6.2
	Internal rotation	7.2	6.7
Subtalar instability	Inversion	12.2	11.3
	Internal rotation	9.8	8.9

## Simulation of tenodesis reconstructions

5 different types of tenodesis reconstruction were simulated in our FE model. The procedures of Pisani ITCL reconstruction[11], Schon CL reconstruction[12] and Choisne CFL reconstruction[13], which recreated a single ligament in the subtalar joint, were simulated in group 1 on a FE model with CFL, CL and ITCL removed. The procedures of Schon triligamentous reconstruction[12] and Mann triligamentous reconstruction[14], which recreated the ATFL, CFL and CL simultaneously, were simulated in group 2 on a FE model with ATFL, CFL, CL and ITCL removed. In clinical approaches, some parts of the graft tendon pass through the bone tunnels in talus, calcaneus and fibula, but this was not simulated in our analysis.

(a) Pisani ITCL reconstruction: The attachment point of the graft on the bone was determined by clinical approaches[11]. One half-peroneus brevis graft was used in this procedure. A double stranded ITCL was recreated between two calcaneal and two talar tunnels. The part of half-peroneus brevis tendon connecting the fifth metacarpal base with calcaneus was also simulated. (Figure.2a)

(b) Schon CL reconstruction: This procedure was simulated based on clinical approaches[12], by using one half-peroneus brevis graft. The CL was recreated between the calcaneus and the talar neck. The part of half-peroneus brevis tendon connecting the fifth metacarpal base with calcaneus was also simulated. (Figure.2b)

(c) Choisne CFL reconstruction: This procedure was simulated based on clinical approaches[13], by using the entire peroneus brevis tendon. The graft passed from the anatomic insertion of CFL on fibula to the attachment on calcaneus. (Figure.2c)

(d) Schon triligamentous reconstruction: This procedure was simulated based on clinical approaches[12], by using the entire peroneus brevis tendon. The ATFL, CFL and CL were recreated simultaneously. The attachment of the graft on the calcaneus, talus and fibula was set on the native insertion of these ligaments. The part of entire peroneus brevis tendon connecting the fifth metacarpal base and calcaneus was also simulated. (Figure.3a)

(e) Mann triligamentous reconstruction: This procedure was simulated based on clinical approaches[14], by using the hamstring tendon. The ATFL, CFL and CL were also recreated simultaneously. The attachment of the graft on the bone was the corresponding anatomic insertion of these three ligaments. (Figure.3b)

## Boundary conditions

To simulate different ankle positions in numerical analysis, the loading condition was applied in two steps. First, the fibula and tibia were flexed at 10° dorsiflexion/plantarflexion or in the neutral position, while the 6 degrees of freedom of the foot were fixed. Then, the 6 degrees of freedom of the tibia and fibula were fixed too, and a rotational moment of 4Nm was applied on the calcaneus. The rotational moment was set to 4Nm, which was the same as a previous cadaveric study of subtalar instability[4]. The internal stress in the ligament was considered to be free in the neutral position of the hindfoot. The

inversion/eversion and internal/external rotation of the subtalar joint were measured at different ankle positions.

## Results

### Group 1(Fig.4)

The section of CFL, ITCL and CL led to obvious instability in the subtalar joint. The inversion, external rotation and internal rotation of the joint all increased at different ankle positions(Fig.4 ). The eversion, however, showed no markedly increase(not shown in figure). All the three procedures improved the stability of subtalar joint in the neutral position, 10° dorsiflexion and 10° plantarflexion. The Choisne CFL reconstruction was most effective in stabilizing the joint. The inversion of the subtalar joint under a rotational moment of 4Nm at the neutral position was 7° for intact, 12.7° for unstable, 10.2° for the Schon, 8.8° for the Pisani and 7.8° for the Choisne, respectively(Fig. 4a). The Pisani ITCL reconstruction exhibited the weakest effect in controlling the internal and external rotation. The internal rotation of the calcaneus at the neutral position was 5.5° for intact, 8.3° for unstable, 6.6° for the Schon, 7.6° for the Pisani and 6.1° for the Choisne, respectively(Fig. 4b). Although the recreation of CFL restored the kinematics of subtalar joint almost to normal, joint laxity still existed.

### Group 2(Fig.5)

The additional section of ATFL only led to a slight increase of motion in the subtalar joint compared to group 1. Although the Schon and Mann triligamentous reconstructions did not recreate the ITCL, these two procedures improved the joint stability very effectively(Fig. 5). The Mann procedure even over-restrained the motion of subtalar joint at all the three ankle positions(Fig. 5). For example, the inversion of subtalar joint at the neutral position was 14.2° for unstable, 6.6° for the Mann and 7.5° for the Schon, respectively(Fig. 5a). The internal rotation of subtalar joint at neutral position was 9.3° for unstable, 5.1° for the Mann and 5.7° for the Schon, respectively(Fig. 5b).

## Discussion

The subtalar joint plays an important role in hindfoot stability. Specifically, the ligamentous contents in the subtalar joint are main structures contributing to its stability. Taillard et al. found that the CFL ruptured first with an inversional force exerted on the cadaveric model, followed by the CL and then the ITCL[27]. Several procedures have been developed for restoring subtalar instability, including CFL reconstruction, CL reconstruction, ITCL reconstruction, and triligamentous reconstruction. However, no comprehensive comparison on their biomechanical behaviors has been conducted yet. In view of this, we compared these 5 representative procedures in this numerical analysis, and the results suggested that the Choisne CFL and Mann triligamentous reconstructions were most effective in stabilizing the subtalar joint.

Previous cadaveric studies have compared the stabilizing effect of different subtalar ligaments. However, which ligament contributes the most remains controversial. The objective of the present study was not to examine the effect of injury in one of the mentioned ligaments. Thus, the ITCL, CFL and CL were removed simultaneously to simulate subtalar instability. Nevertheless, the results of different tenodesis reconstructions can reflect the contribution of these ligaments.

ITCL is a V-shaped ligament composed of two bands, with the fiber oriented from superomedial to inferolateral[17]. It occupies nearly half of the medial part of the tarsal canal. There is still no agreement regarding the mechanical contribution of ITCL to subtalar instability. Some researchers compared it with the cruciate ligaments of the knee in terms of the stabilizing effect on the subtalar joint[11, 28]. Knudson reported that the ITCL contributed substantially to supination stability[29]. Tochigi et al. suggested that the ITCL restrained the subtalar joint in inversion and prevented anteromedial displacement[30]. However, several publications questioned the importance of the ITCL[4, 6]. For example, Li et al. pointed out that the most important ligament of the tarsal sinus was the CL, while the ITCL, although always present, was a thin single-band ligament[31]. Smith and Cahill[32, 33]highlighted that the ITCL was not an important component for subtalar stability. In our simulation, the Pisani ITCL reconstruction was found to reinforce the inversional stability, but had little effect on rotational stability. Tochigi suggested that the ITCL counteracted against the drawer force on the calcaneus[30]. The ITCL was located between the posterior and middle facet of the subtalar joint, similar to the cruciate ligaments of the knee. The cruciate ligaments mainly restrain the anterior and posterior translation of the tibia. Similarly, the ITCL may primarily restrain the translational displacement of calcaneus, but contribute little to rotational stability.

The CL is another important ligament of the subtalar joint. Its fiber is oriented from the superolateral calcaneal surface to an inferolateral tubercle on the talus neck. Some researchers believed that the CL was more important than the ITCL in stabilizing the subtalar joint[2, 3, 31]. Earlier studies found that the CL could restrain the inversion and external rotation of the subtalar joint[7, 32, 33]. Our study also revealed that the Schon CL reconstruction contributed more to the rotational stability than the ITCL reconstruction did, but its effect on inversional stabilization was the weakest of the three procedures.

The CFL originates from the fibular tip to the lateral posterior calcaneus and bridges the posterior facet of the subtalar joint subtalar joint. It is widely accepted as an important ligament for ankle stabilization, and its function in relation to subtalar stability has been gradually revealed and confirmed in recent years. Weindel and Karlsson supposed that the CFL played a key role in subtalar stability[3, 6]. Choisne et al. reported that subtalar instability occurred after section of CFL in isolation in their experiment[34]. Pellegrini et al. found that the CFL disruption could lead to an increase in inversion and external rotation, which might be detectable during a manual examination[4]. Our study showed that the Choisne CFL reconstruction was more effective than the Pisani ITCL and Schon CL reconstructions in alleviating the instability of subtalar joint. However, the Choisne CFL reconstruction needs to use the entire peroneus brevis tendon as graft, while the Pisani ITCL and Schon CL reconstructions use only half of a peroneus brevis tendon. This may enhance the stabilizing effect of Choisne CFL reconstruction.

For subtalar instability usually coexists with lateral ankle instability[1, 2], the triligamentous reconstruction procedure was developed for recreating the ATFL, CFL and CL. In our simulation, the triligamentous reconstruction improved the subtalar stability very effectively without recreating the ITCL. The results showed that the Mann procedure had a stronger correcting power in controlling subtalar instability than the Schon procedure did. This may be attributed to the difference in their grafts(the Mann procedure uses semitendinosus brevis tendon as graft, while the Schon procedure uses peroneus brevis tendon as graft). The elastic modulus and cross-sectional area of semitendinosus are 1036MPa and 20mm<sup>2</sup>, respectively[35, 36]. The peroneus brevis tendon has an elastic modulus value of 149.7 MPa and a cross-sectional area of about 19.5mm<sup>2</sup>[25]. Obviously, the strength of semitendinosus is much higher than that of peroneus brevis tendon. However, according to our simulation results, the hamstring tendon is so stiff that it restrains the mobility of the subtalar joint. This might result in detrimental long-term effects on the cartilage[37]. On the other hand, the peroneus brevis tendon is somewhat elastic for the subtalar joint and the model remains a certain degree of laxity under the Schon procedure. The ideal graft should have the same material properties as the native ligament and mimic the same biomechanical behaviors as the original joint[35]. Therefore, both types of graft have defects.

In general, although several experiments have evaluated the biomechanical function of subtalar ligaments, the conclusions remain controversial. Therefore, there is no consensus on which ligament should be recreated first by the tenodesis procedure. At the same time, the injury mechanism and clinical manifestation of subtalar instability are similar to that of ankle instability, and therefore, its diagnosis is often misinterpreted. As a result, the publications of surgical reconstruction regarding subtalar instability are very limited. There is no comprehensive comparison targeting the correcting power of these tenodesis procedures so far. The results of our study showed that none of these tenodesis procedures could restore the biomechanical behaviors of the subtalar joint to normal. Fortunately, the stability of subtalar joint was supported by the bony geometry and ligaments jointly. In a cadaveric research on hindfoot stability, Cass et al. found that the subtalar joint appeared to be stable when the foot was loaded, and they believed that the stability of subtalar joint largely came from the bony constrains[38]. In our simulation, the subtalar joint was loaded without weight bearing. In this condition, the tested procedures still managed to restore the subtalar stability effectively. Even though the joint was subject to a certain degree of postoperative laxity, with the inherent stability of the joint surface congruency, the subtalar instability would be further improved in weight bearing.

There are several limitations in the present study. First, some simplifications were introduced in our model. The material properties of the ligaments and grafts were determined in accordance with the literature rather than actual measurements. Different material models were used for soft tissues, including both linear hyperelastic and non-linear hyperelastic models, and the viscoelastic properties of the soft tissues were not considered. Moreover, the parts of the grafts that pass through the bone tunnels were also simplified. Despite these simplifications, the validation test showed that our simulation results were very close to the experimental measurements of previous cadaveric studies. Second, our simulation only evaluated the immediate postoperative stability of the targeted procedures, while the long-term

stability still warrants further research. As we know, the grafts need to experience a process of revascularization and remodeling after surgery[39], in which, the alignment of the fibroblast and collagen bundles in the grafts is regained and becomes similar to that of the normal ligament. Therefore, the material properties of the grafts would gradually change, which would further impact the long-term stability of the joint. However, the findings on the immediate postoperative stability are still valuable for us to evaluate different rehabilitation plans for these procedures.

## Conclusions

In the present study, our numerical analysis showed that the Choisine CFL reconstruction and Mann triligamentous reconstruction provided the greatest degree of immediate postoperative subtalar stability. However, both procedures could not restore the biomechanical behaviors of the subtalar joint to normal. The long-term efficacy of these procedures still warrants further investigation using a substantially larger sample of clinical cases.

## List Of Abbreviations

ITCL: interosseous talocalcaneal ligament; CL: cervical ligament; CFL: calcaneofibular ligament; ATFL: anterior talofibular ligament; NURBS: non-uniform rational B-spline; CT: computerized tomography; MRI: magnetic resonance imaging

## Declarations

**Acknowledgements**Not Applicable.

## Funding

This study was supported by the Natural Science Foundation Project of China(No. 81301543)

## Availability of data and materials

All data and materials are available from the corresponding author with reasonable requirement.

## Authors' contributions

CX performed the finite element analysis, MQL and CGW are responsible for manuscript writing, and HL contributed for the experimental design and manuscript revision. All authors have read and approved the final manuscript.

## Authors' information

All authors come from the Department of Orthopaedic Surgery, Xiangya Hospital, the Central South University, No. 87, Xiangya Street, Changsha 401008, China.

## Ethics approval and consent to participate

The study had been approved by Ethics Committee of Xiangya Hospital and a written consent was obtained from the participant in CT acquisition.

## Consent for publication

Not applicable.

## Competing interests

All authors declare that they have no competing interests.

## References

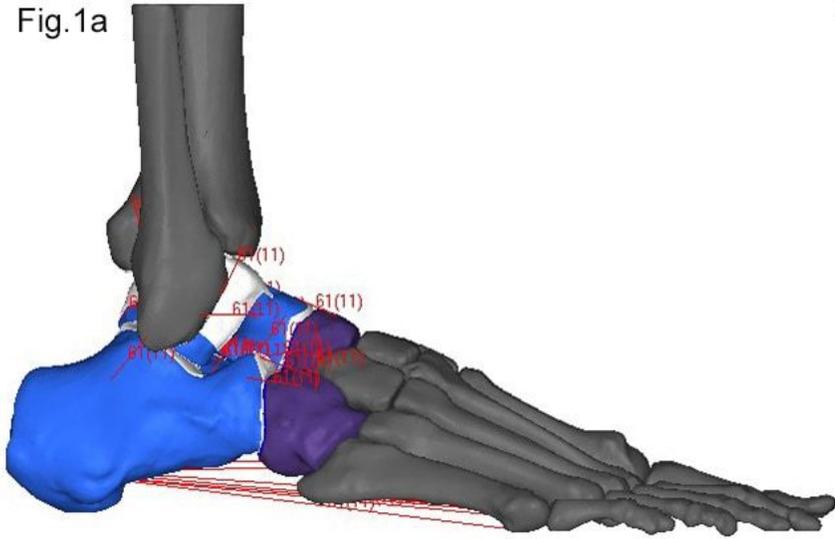
1. Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *Journal of athletic training*. 2002; 37:364-375.
2. Meyer JM, Garcia J, Hoffmeyer P, Fritschy D. The subtalar sprain. A roentgenographic study. *Clinical orthopaedics and related research*. 1988; 226:169-173.
3. Karlsson J, Eriksson BI, Renstrom PA. Subtalar ankle instability. A review. *Sports medicine*. 1997; 24:337-346.
4. Pellegrini MJ, Glisson RR, Wurm M, Ousema PH, Romash MM, Nunley JA, 2nd, Easley ME. Systematic Quantification of Stabilizing Effects of Subtalar Joint Soft-Tissue Constraints in a Novel Cadaveric Model. *The Journal of bone and joint surgery American volume*. 2016; 98:842-848.
5. Tochigi Y, Takahashi K, Yamagata M, Tamaki T. Influence of the interosseous talocalcaneal ligament injury on stability of the ankle-subtalar joint complex—a cadaveric experimental study. *Foot & ankle international*. 2000; 21:486-491.
6. Weindel S, Schmidt R, Rammelt S, Claes L, v Campe A, Rein S. Subtalar instability: a biomechanical cadaver study. *Archives of orthopaedic and trauma surgery*. 2010; 130:313-319.
7. Kjaersgaard-Andersen P, Wethelund JO, Helmig P, Soballe K. The stabilizing effect of the ligamentous structures in the sinus and canalis tarsi on movements in the hindfoot. An experimental study. *The American journal of sports medicine*. 1988; 16:512-516.
8. Elmslie RC. Recurrent Subluxation of the Ankle-Joint. *Annals of surgery*. 1934; 100:364-367.
9. Chrisman OD, Snook GA. Reconstruction of lateral ligament tears of the ankle. An experimental study and clinical evaluation of seven patients treated by a new modification of the Elmslie procedure. *The Journal of bone and joint surgery American volume*. 1969; 51:904-912.
10. Brattstrom H. Tenodesis employing the method of Watson-Jones for the treatment of recurrent subluxation of the ankle. *Acta Orthop Scand*. 1953; 23:132-136.
11. Pisani G. Chronic laxity of the subtalar joint. *Orthopedics*. 1996; 19:431-437.

12. Schon LC, Clanton TO, Baxter DE. Reconstruction for subtalar instability: a review. *Foot & ankle*. 1991; 11:319-325.
13. Choisne J, Hoch MC, Alexander I, Ringleb SI. Effect of Direct Ligament Repair and Tenodesis Reconstruction on Simulated Subtalar Joint Instability. *Foot & ankle international*. 2017; 38:324-330.
14. Thomas O. Clanton, Waldrop NE. Athletic Injuries to the Soft Tissues of the Foot and Ankle. In: Coughlin MJ, Saltzman CL, Anderson RB, editors. *Mann's Surgery of the Foot and Ankle*. Mosby; 2013: 1607.
15. Xu C, Li MQ, Wang C, Liu H. Nonanatomic versus anatomic techniques in spring ligament reconstruction: biomechanical assessment via a finite element model. *Journal of orthopaedic surgery and research*. 2019; 14:114.
16. Golano P, Vega J, de Leeuw PA, Malagelada F, Manzanares MC, Gotzens V, van Dijk CN. Anatomy of the ankle ligaments: a pictorial essay. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA*. 2016; 24:944-956.
17. Kelilian AS, SK S. *Sarrafan's Anatomy of the Foot and Ankle*. 3rd ed. Philadelphia: Wolters Klover Health, LWW; 2011.
18. Funk JR, Hall GW, Crandall JR, Pilkey WD. Linear and quasi-linear viscoelastic characterization of ankle ligaments. *Journal of biomechanical engineering*. 2000; 122:15-22.
19. Siegler S, Chen J, Schneck CD. The three-dimensional kinematics and flexibility characteristics of the human ankle and subtalar joints–Part I: Kinematics. *Journal of biomechanical engineering*. 1988; 110:364-373.
20. Mkandawire C, Ledoux WR, Sangeorzan BJ, Ching RP. Foot and ankle ligament morphometry. *Journal of rehabilitation research and development*. 2005; 42:809-820.
21. Shin J, Yue N, Untaroiu CD. A finite element model of the foot and ankle for automotive impact applications. *Annals of biomedical engineering*. 2012; 40:2519-2531.
22. Cheung JT, An KN, Zhang M. Consequences of partial and total plantar fascia release: a finite element study. *Foot & ankle international*. 2006; 27:125-132.
23. Kitaoka HB, Luo ZP, Growney ES, Berglund LJ, An KN. Material properties of the plantar aponeurosis. *Foot & ankle international*. 1994; 15:557-560.
24. Anderson AE, Ellis BJ, Maas SA, Peters CL, Weiss JA. Validation of finite element predictions of cartilage contact pressure in the human hip joint. *Journal of biomechanical engineering*. 2008; 130:051008.
25. Bohnsack M, Surie B, Kirsch IL, Wulker N. Biomechanical properties of commonly used autogenous transplants in the surgical treatment of chronic lateral ankle instability. *Foot & ankle international*. 2002; 23:661-664.
26. Weiss JA, Gardiner JC, Bonifasi-Lista C. Ligament material behavior is nonlinear, viscoelastic and rate-independent under shear loading. *Journal of biomechanics*. 2002; 35:943-950.
27. Taillard W, Meyer JM, Garcia J, Blanc Y. The sinus tarsi syndrome. *Int Orthop*. 1981; 5:117-130.

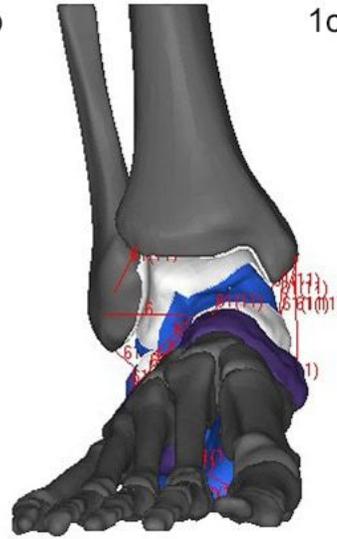
28. Pisani G, Pisani PC, Parino E. Sinus tarsi syndrome and subtalar joint instability. *Clinics in Podiatric Medicine & Surgery*. 2005; 22:63-77.
29. Knudson GA, Kitaoka HB, Lu C-L, Luo ZP, An K-N. Subtalar joint stability: Talocalcaneal interosseous ligament function studied in cadaver specimens. *Acta Orthopaedica Scandinavica*. 1997; 68:442-446.
30. Tochigi Y, Amendola A, Rudert MJ, Baer TE, Brown TD, Hillis SL, Saltzman CL. The Role of the Interosseous Talocalcaneal Ligament in Subtalar Joint Stability. *Foot & ankle international*. 2004; 25:588-596.
31. Li SY, Hou ZD, Zhang P, Li HL, Ding ZH, Liu YJ. Ligament structures in the tarsal sinus and canal. *Foot & ankle international*. 2013; 34:1729-1736.
32. Cahill DR. The anatomy and function of the contents of the human tarsal sinus and canal. *Anatomical Record*. 1965; 153:1-17.
33. Smith JW. The ligamentous structures in the canalis and sinus tarsi. *Journal of Anatomy*. 1958; 92:616-620.
34. Choisne J, Hoch MC, Bawab S, Alexander I, Ringleb SI. The effects of a semi-rigid ankle brace on a simulated isolated subtalar joint instability. *Journal of Orthopaedic Research*. 2013; 31:1869-1875.
35. Smeets K, Bellemans J, Scheys L, Eijnde BOOT, Claes S. Mechanical Analysis of Extra-Articular Knee Ligaments. Part two: Tendon grafts used for knee ligament reconstruction. *Knee*. 2017; 24:957-964.
36. Handl M, Drzík M, Cerulli G, Povysil C, Chlpík J, Varga F, Amler E, Trc T. Reconstruction of the anterior cruciate ligament: dynamic strain evaluation of the graft. *Knee Surgery Sports Traumatology Arthroscopy Official Journal of the Esska*. 2007; 15:233-241.
37. Fu FH, Herbst E. Editorial Commentary: The Pivot-Shift Phenomenon Is Multifactorial. *Arthroscopy the Journal of Arthroscopic & Related Surgery*. 2016, 32:1063-1064.
38. Cass JR, Morrey BF, Chao EY. Three-dimensional kinematics of ankle instability following serial sectioning of lateral collateral ligaments. *Foot & ankle*. 1984, 5:142-149.
39. Shino K, Kawasaki T, Hirose H, Gotoh I, Inoue M, Ono K. Replacement of the anterior cruciate ligament by an allogeneic tendon graft. An experimental study in the dog. *J Bone Joint Surg Br*. 1984; 66:672-681.

## Figures

Fig. 1a



1b



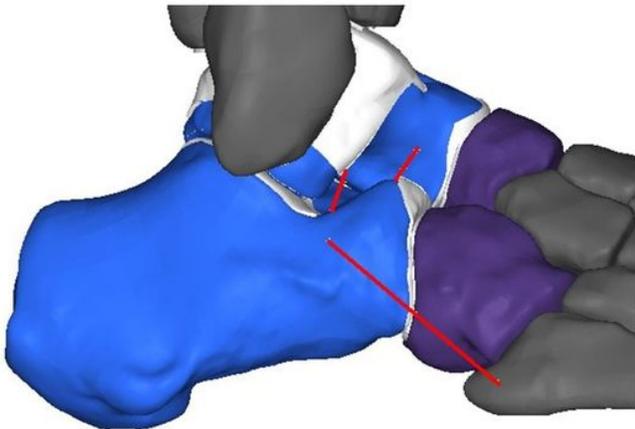
1c



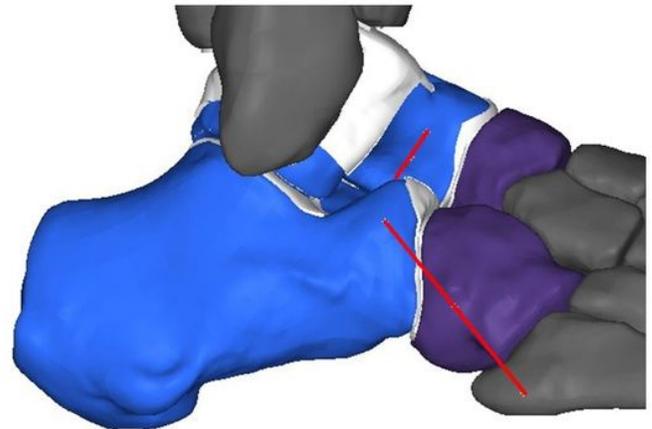
Figure 1

The FE model: (a) lateral view, (b) front view, (c) bottom view

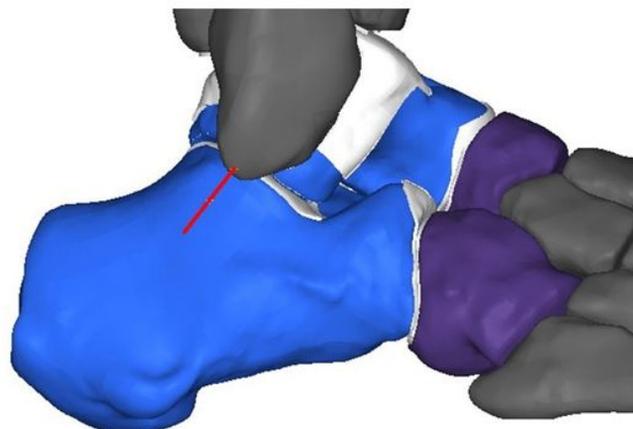
Fig. 2a Pisani ITCL reconstruction



2b Schon CL reconstruction



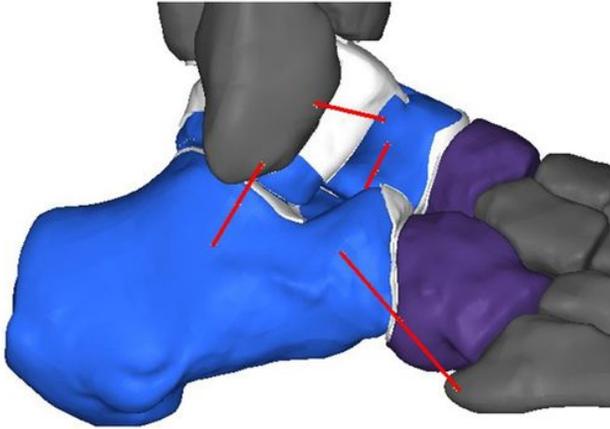
2c Choisine CFL reconstruction



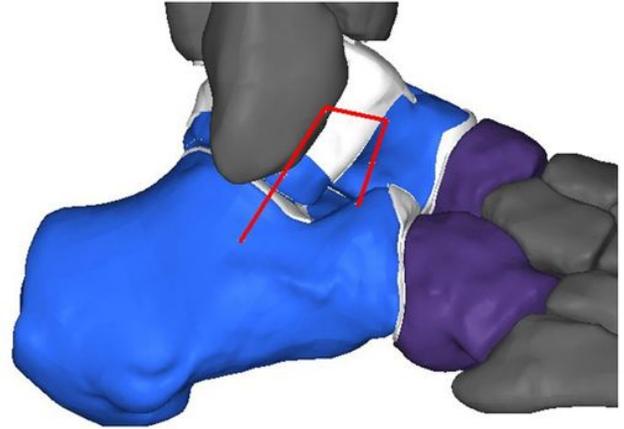
## Figure 2

Single ligament reconstruction: three models with reconstructed tendon grafts: (a) Pisani ITCL reconstruction by using one half-peroneus brevis graft, (b) Schon CL Reconstruction by using one half-peroneus brevis graft, and (c) Choisine CFL reconstruction by using entire peroneus brevis tendon

Fig.3a Schon triligamentous reconstruction



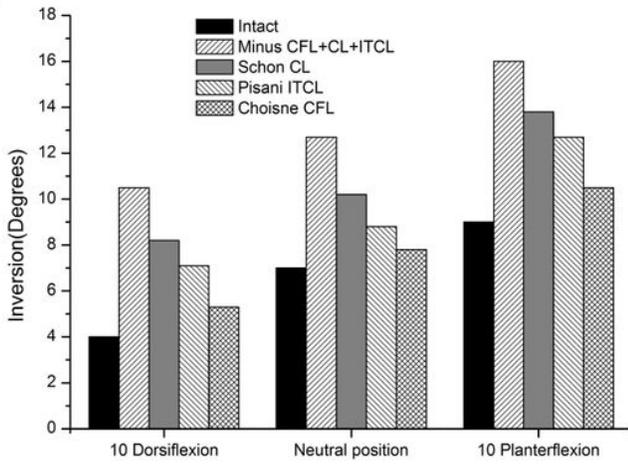
3b Mann triligamentous reconstruction



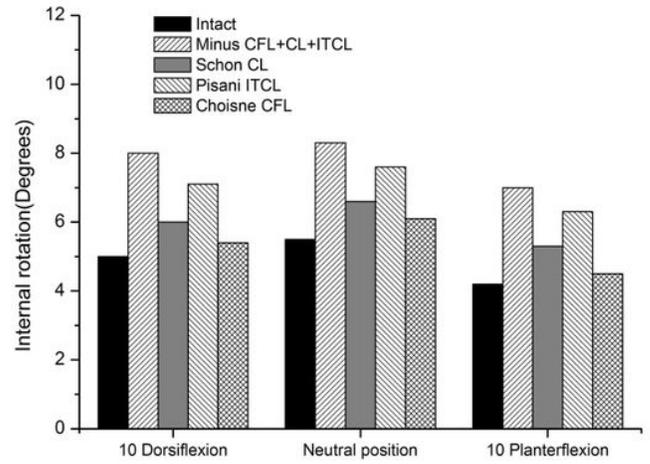
## Figure 3

Triligamentous reconstruction: (a) Schon triligamentous reconstruction by using entire peroneus brevis tendon, (b) Mann triligamentous reconstruction by using hamstring tendon

Fig.4a



4b



4c

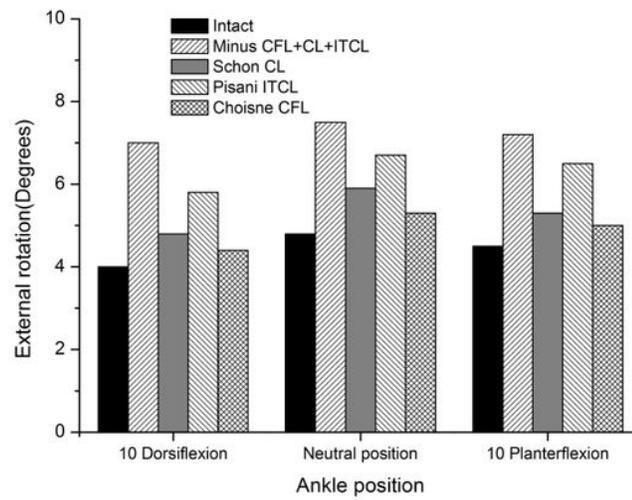
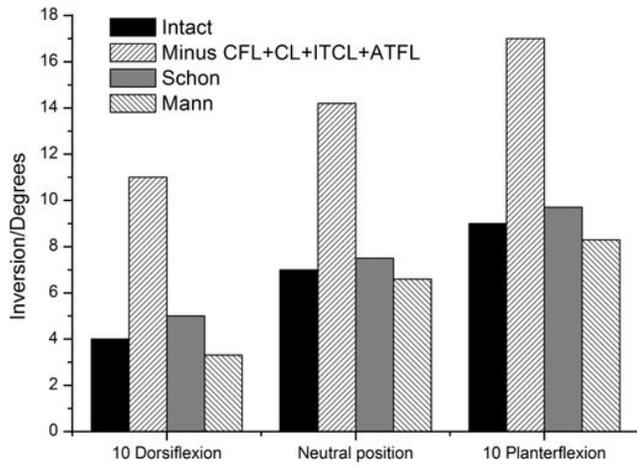


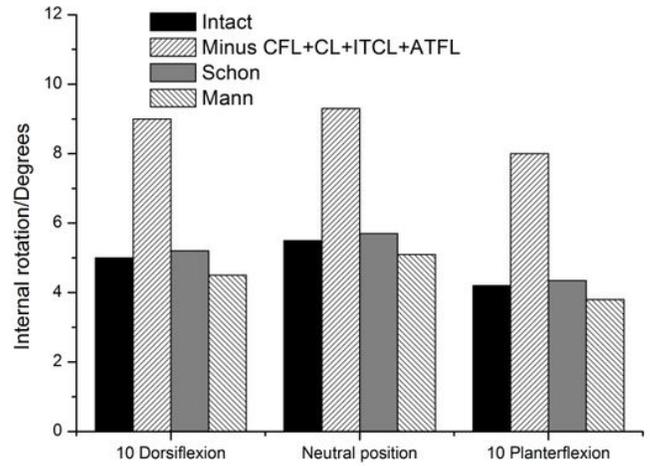
Figure 4

Range of (a)inversion, (b)internal rotation and (C)external rotation at the subtalar joint in the intact condition; after sectioning the ITCL, CFL and CL; after performing the Schon CL reconstruction; after performing the Pisani ITCL reconstruction; and after performing the Choisne CFL reconstruction in different ankle position.

Fig.5a



5b



5c

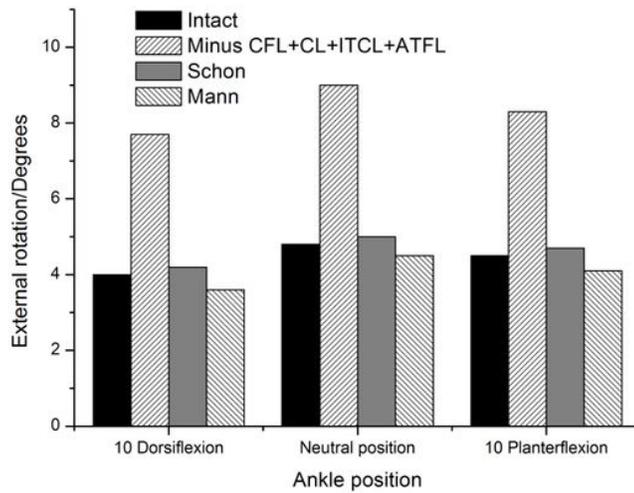


Figure 5

Range of (a)inversion, (b)internal rotation and (C)external rotation at the subtalar joint in the intact condition; after sectioning the ATFL, ITCL, CFL and CL; after performing the Schon triligamentous reconstruction; and after performing the Mann triligamentous reconstruction in different ankle position.