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Biomechanical evaluation of syndesmotic fixation techniques via finite element analysis: screw vs. suture button

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HIGHLIGTHS

- Syndesmotic injured fixation using a 3D finite element model.
- Important biomechanical differences between screws and suture buttons.
- Suture button behavior closer to the intact ankle joint
- Preoperative planning tool for surgery support

Abstract

Background and Objective: Tibiofibular syndesmotic injuries may cause degenerative changes, reduction in ankle function and compromising ankle stability. Different fixation techniques try to restore its functionality. Screw-fixation is the gold-standard. Recently, suture-button fixation has aroused the attention because it allows for physiologic micromotion while maintaining an accurate reduction. The aim of this study is to compare the biomechanical behaviour of both fixation techniques using the finite element method.

Methods: A three-dimensional finite element model of the tibiofibular joint was reconstructed simulating the intact ankle and the injured syndesmosis. Then, different methods of syndesmosis fixation were analysed: screws (number of cortices, number of screws and distance between screws) and suture buttons (single, double parallel and double divergent with a sensitivity analysis on the pretension forces) configuration. Ligaments and cartilages were included and simulated as spring elements. Physiological loads during stance phase were simulated.

Results: Syndesmosis widening and von Mises stresses were computed. Syndesmosis widening in the injured configuration compromised joint stability (2.06 mm), whereas using a single quadricortical screw (0.18 mm) stiffened the joint. Syndesmosis widening using suture-buttons were closer to syndesmosis widening of the intact ankle configuration (0.97 mm). Von Mises stresses were higher for the titanium screws than for the suture buttons.

Conclusions: A detailed biomechanical comparison among different syndesmotic fixation was performed. Suture buttons have advantages with regard to syndesmosis widening in comparison to screw fixation. This fact supports the good long-term clinical results obtained with suture buttons fixation. The proposed methodology could be an efficient tool for preoperative planning.

Keywords

syndesmotic injuries, finite element analysis, screw, suture button, biomechanical behaviour, syndesmosis widening

1. Introduction

Recent studies show that tibiofibular syndesmosis injuries are an underdiagnosed issue usually camouflaged by the habitual symptoms of ankle sprains (Fort et al., 2017). Between 1 and 11% of these sprains are actually tibiofibular syndesmosis injuries, being especially significant in sports activities that imply high impact (Van Heest and Lafferty, 2014; Shore and Kramer, 2016). This kind of injuries can be caused along with a fibula fracture or just as a consequence of an external rotation of the ankle at the inferior tibiofibular joint.These injuries may lead the tibiofibular syndesmosis to a stress situation that may worsen by the foot external rotation (Fort et al., 2017; Yuen and Lui 2017). Among the regions susceptible to suffer any damage when an isolated syndesmotic injury occurs, anterior tibiofibular ligament and intraosseous membrane are the most usually affected ligaments. Syndesmotic injury may lead to a partial or, in the case of the anterior ligament, total rupture of the ligament (Rammelt and Obruba, 2015; Schepers et al., 2014; Fort et al., 2017).

Different surgical procedures can be considered when instability occurs in the syndesmosis sprain (Fort et al., 2017; de las Heras-Romero et al. 2017). Traditionally, screws inclusion has been the most common solution (Rammelt and Obruba, 2015; Stuart and Panchbhavi, 2011). In this procedure, screws are placed as a union between the fibula and the tibia drilling through the complete fibular bone and partially (tricortical fixation) or totally (quatricortical fixation) the tibial bone (Schepers et al., 2014). As stability element for the screw inclusion, a plate is also fixed with shorter screws to the fibular bone. This fixation is usually performed including one or two screws in the tibiofibular union. The type of screws used in this fixation uses to be titanium. The main disadvantage of using titanium screws is that they need to be removed. In the last years, the option of including bioabsorbable screws has also appeared (Rammelt and Obruba, 2015). Suture button procedure has also gained relevance as an alternative for the screws inclusion (Westermann et al., 2014; Rigby and Cottom, 2013). In the suture button process the fixation rope or ropes, depending on the selected solution, are also placed by drilling both bones, and are placed with the use of small plates where the ropes are tied. When placed in the desired position, the ropes are tightened; partially restraining the relative displacement of the bones (Westermann et al., 2014). This surgical procedure allows a less limited motion of the joint and in most cases is not removed after the surgery unless the patient reports any issue derived from its use (Parker et al., 2018). Also, the absence of titanium in the intraosseous fixation allows obtaining better results in posterior scans required in the affected region (Westermann et al., 2014). The comparison between these two techniques has been previously analysed in several clinical or cadaveric studies (Naqvi et al., 2012; Schepers 2012; Laflamme et al., 2015; Schon et al., 2016; Clanton et al., 2016; Zhang et al. 2017; Neary et al., 2017; Xie et al., 2018; Raeder et al., 2020), but there is not a clinical consensus about the higher reliability of one technique over the other.

Previous biomechanical studies in cadaveric specimens gave a good overview of syndesmotic injuries and the different surgical procedures. However, it is difficult to compare the findings among different studies and quantify stresses, displacements, etc. Additional, cadaveric studies are costly, time-consuming and some cases inefficient. To solve this problem, computational tools based on the finite element method may help to predict the biomechanical behaviour of the joint. The usefulness of finite element (FE) models in biomechanical analyses has been widely proven for the simulation of patient-specific ankle joints or the prediction of mechanical function (Liacouras and Wayne, 2007). This methodology has been also used for analysing surgical solutions for the tibiofibular syndesmosis injuries (Liu et al., 2013, 2016; Serhan et al., 2013; Verim et al., 2014; Serhan et al., 2015). Liu et al. (2013, 2016) demonstrated that a transverse syndesmotic screw can effectively control excessive abnormal activity of the distal tibia and fibula after tibiofibular syndesmosis injury. Screw fixation also affected the physiological normality of the joint, leading to decreased magnitude of motion at the lower extremes of the tibia and fibula, reduced contact forces between bones and increased stress on the proximal interosseous membrane. Serhan et al. (2013) compared different screw sizes, number of cortices and number of screws needed. They concluded that quatricortical application of 3.5-mm single screws and tricortical application of 3.5-mm double cortical screws were not good choices for syndesmosis fixation. Verim et al. (2014) observed that syndesmosis fixation at the level of 30-40 mm above tibiotalar joint had advantages with regard to stress in screws in comparison with other evaluated levels. Finally, Serhan et al. (2015) investigated which geometric screw parameters played key roles in stresses that occur in screws used for syndesmotic fixation. None of previous FE studies compare the performance of screws against suture buttons which are growing in popularity (Parker et al., 2018). Additionally, the performance of suture buttons using a finite element analysis has not been previously studied.

Therefore, the main goal of the present study is to compare the biomechanical behaviour of different syndesmotic fixations: screws (diameter, number of cortices, number of screws and distance between screws) versus suture buttons (single, double parallel and double divergent) with different pretension forces. Titanium screws will be considered. Suture button with the characteristics of the Tightrope® implant (Arthrex) will be simulated. For a better comparison between the surgical solutions and the effect of this injury, the study will include the analysis of the healthy and injured states of the joint. With this aim, a FE analysis will be developed based on the anatomical model of an ankle joint from a real patient. The present study will analyse these procedures from a biomechanical perspective using computational tools.

2. Material and Methods

A three-dimensional (3D) solid model of the left ankle of a male patient (56 years old, 80 kg) was reconstructed. The model consisted of bones, cartilage and ligaments, muscles were not simulated. Bones were modeled following the 3D reconstruction obtained from a computed tomography (CT) scan (Figure 1a). The images were acquired using a 64-detector multidetector computerized tomography (MDCT) system (Brilliance 64, Philips Healthcare, Amsterdam, The Netherlands) using a tube current of 257 mA and a voltage of 120 kV. The spatial resolution was 0.65 x 0.65 mm, with a reconstructed matrix of 768 x 768. The slice thickness was 2 mm. CT images were imported in the software Mimics (Materialise NV, Leuven, Belgium) and processed in order to get a surface representation containing the structure of the three bones required for this study: tibia, fibula and talus. The files were loaded in 3-Matic (Materialise NV, Leuven, Belgium) in order to generate the mesh for the FE analysis. Bone mesh size was selected to be as accurate as possible with the same size in all three bones. After performing a mesh sensitivity analysis with values between 2 and 3 mm for edge lengths, mesh size was set to 3 mm (Figure 1b). Cortical bone was modeled as a shell with a constant thickness of 3mm. The cortical thickness was measured in the CT scan and an average thickness of 3 mm was computed. Trabecular bone was created using lineal tetrahedral elements. Edge size for these elements was also set to 3 mm.

Once the structure of the model was defined, the file containing the geometry was imported in the software Abaqus/CAE 6.19 (Dassault Systèmes, France). Then, ligaments and cartilages were included and simulated as spring elements. Cartilages were included as a set of springs with a stiffness of 13.49 N/mm, obtained as the mean value of the ankle cartilage compression response defined by the study of Shepherd and Seedhom (1999). Ligaments were also included as a set of springs following a similar configuration to the one used by Liacouras and Wayne (2007) in their study (Figure 1c). The stiffness values of ligaments and number of springs used are listed in Table 1.

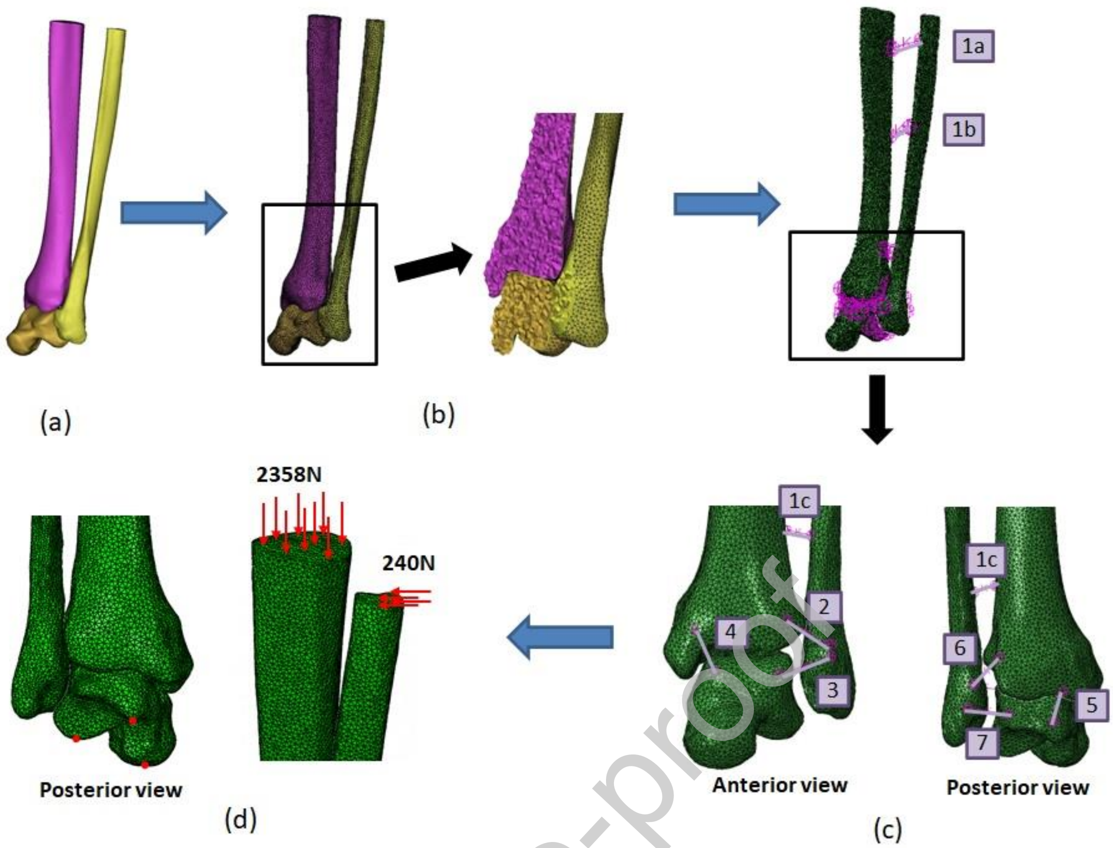

Figure 1. Workflow for the finite element simulations of the syndesmotic injury: (a) 3D bone reconstruction; (b) finite element mesh generated; (c) final model including the ankle joint ligaments using springs: (1a,1b,1c) Interosseous Membrane (IM), (2) Anterior Tibiofibular Ligament (ATL), (3) Anterior Talofibular Ligament (ATFL), (4) Anterior Tibiotalar Ligament (ATTL), (5) Posterior Tibiotalar Ligament (PTTL), (6) Posterior Tibiofibular Ligament (PTL) and (7) Posterior Talofibular Ligament (PTFL); (d) Boundary and loading conditions applied to the model.

Ligament	Stiffness (N/mm)*	Number of Springs
Anterior Tibiofibular Ligament (ATL)	90	1
Posterior Tibiofibular Ligament (PTL)	90	2
Interosseous Membrane (IM)	134	3
Anterior Talofibular Ligament (ATFL)	90	1
Posterior Talofibular Ligament (PTFL)	70	1
Anterior Tibiotalar Ligament (ATTL)	70	1
Posterior Tibiotalar Ligament (PTTL)	80	1

*Table 1. Distribution of the ligaments included in the FE model. *Stiffness indicates the value for every individual spring in the ligament.*

Cortical and trabecular bone structures were assumed to be isotropic, homogeneous and linearly elastic. The Young modulus values and Poisson ratios of materials used in the analysis are listed in Table 2 (Serhan et al., 2013, 2015; Verim et al., 2014).

Material	Young Modulus (MPa)	Poisson Ratio
Cortical Bone	17000	0,3
Trabecular Bone	700	0,3
Titanium	107000	0,34
UHMWPE – suture button	*928,5*	*0,35*

Table 2. Mechanical properties of bones of the ankle joint and screw and suture button materials used in the different FE models.

Boundary conditions and loads were included in the model (Figure 1d). The ankle joint was fixed to the floor through three nodes of the lower surface of the talus bone. Physiological loads during stance phase normal walking were simulated (Serhan et al., 2013, 2015; Verim et al., 2014). Compressive force (2358 N) was applied at the proximal tibia and tangential force (240N) was applied medially at the proximal fibula.

In this study, different simulations were performed to analyse the intact ankle, injured syndesmosis and different methods of syndesmosis fixation (Figures 2 and 3). First, the intact ankle was simulated (Figure 2a). Then, the injured syndesmosis was simulated by removing the Anterior Tibiofibular Ligament (ATL) spring (Figure 1c – 6) and the lower spring of the Intraoseous Membrane (IM) (Figure 1c – 1c) (Rammelt and Obruba, 2015; Schepers et al., 2014; Fort et al., 2017), leaving free the lower connection between tibia and fibula (Figure 2b). Then, two different methods of syndesmosis fixation were considered: titanium screws (Figure 2c-f) and suture buttons (Figure 3).

Screws were modeled as beam elements (B33 - Abaqus/CAE 6.19) of 3.5mm diameter and titanium material properties (Table 2) (Thompson and Gesink, 2000; Serhan et al., 2015; Liu et al., 2016). One (single) screw was simulated with a tricortical fixation (Figure 2c) or with a rigid quadricortical fixation (Figure 2d). In both cases, the screw was placed 45 mm above the tibiotalar joint. The impact of using two (double) screws (tricortical – Figure 2e and quadricortical – Figure 2f) for the fixation was also considered studying the effect of the distance between screws (10mm, 15mm and

18mm). The top screw was always placed 45 mm above the tibiotalar joint (Verim et al., 2014).

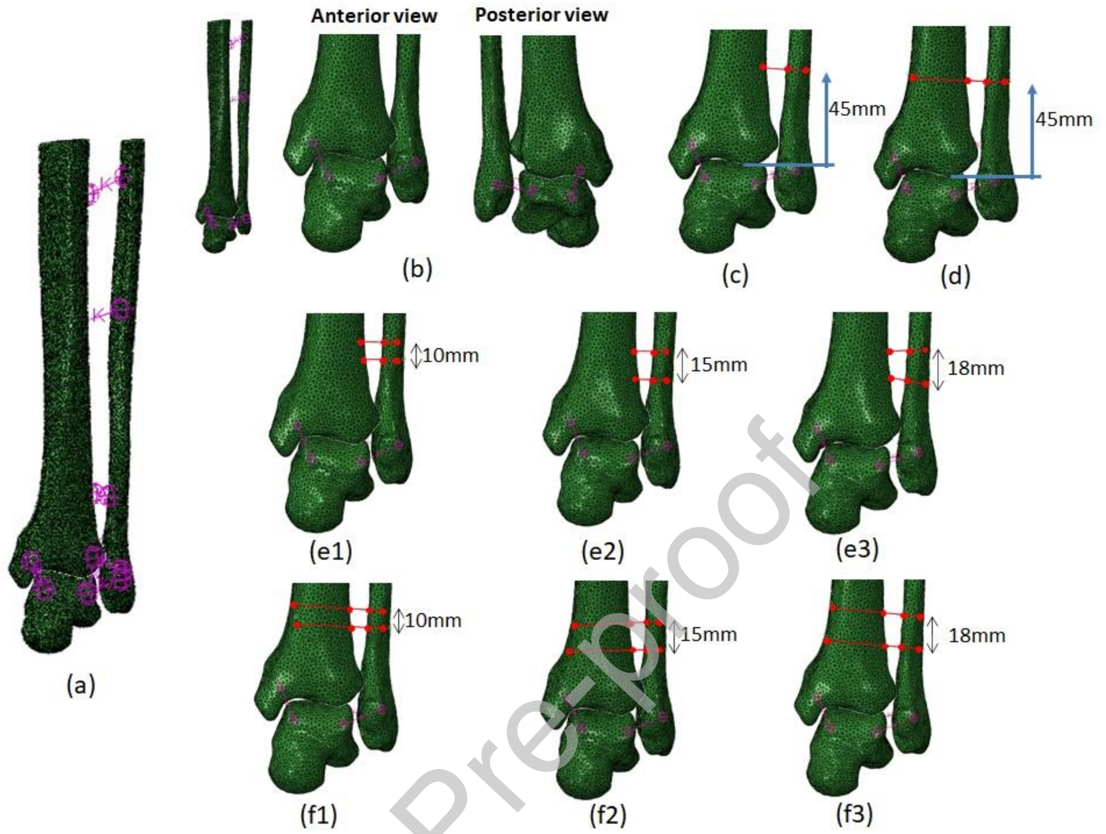

Figure 2. FE models analysed. (a) Intact ankle; (b) injured syndesmosis; (c) single tricortical screw; (d) single quadricortical screw; (e1) double tricortical with 10mm distance; (e2) double tricortical with 15mm distance; (e3) double tricortical with 18mm distance; (f1) double quadricortical with 10mm distance; (f2) double quadricortical with 15mm distance; (f3) double quadricortical with 18mm distance.

Suture buttons were also modeled as beam elements (B33 - Abaqus/CAE 6.19) of 3.0mm diameter and ultra-high-molecular-weight polyethylene (UHMWPE) material properties (Table 2) (Figure 3). These properties resembled the characteristics of the Tightrope® implant (Arthrex). Three different configurations were modeled: a single suture button (Figure 3a), two suture buttons in parallel orientation in the axial plane (Figure 3b) and two suture buttons with approximately 20º of divergence in the axial plane (Figure 3c). The single and top suture buttons were placed 45mm above the tibiotalar joint. Distance between the two suture buttons was 10mm (Figures 3b-c). In the clinical practice, a tensiometer is used to tension each strand of the knotless kit to approximately 80N (Westermann et al., 2014, Zhang et al., 2017). This mechanical state was simulated through a pretension applied to the beam elements modelling the suture buttons. A sensitivity analysis with different pretension forces was carried out: 20N, 30N, 40N, 80N and 100N.

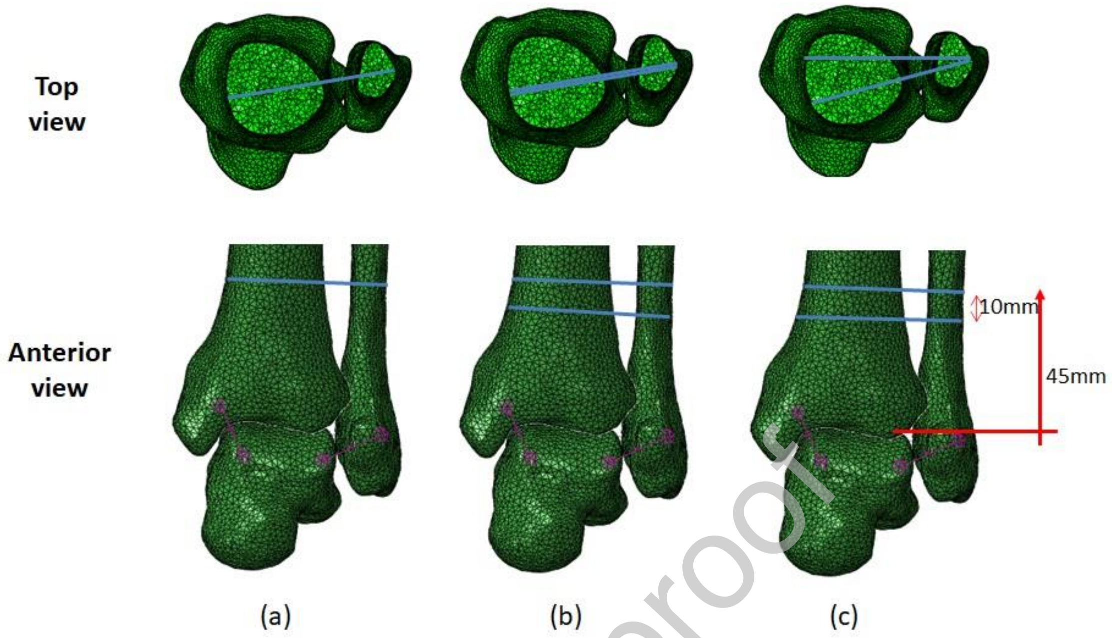

Figure 3. Orientation of the fixation for the single, parallel, and divergent configurations using suture buttons from the top and anterior view.

As the main goal of the syndesmotic fixation is to maintain the distal tibiofibular joint in a reduced position during healing, the syndesmosis widening was evaluated in every case (healthy, injured and with screw/suture button fixation). At the end of the finite element analyses, the syndesmosis widening was the relative distance between the tibia and fibula at the level of the screw/suture button location after and before loading. The syndesmosis widening was measured 45mm above the tibiotalar joint. Additionally, von Mises stresses on the screws and suture buttons were evaluated.

3. Results

3.1.Syndesmosis widening

Syndesmosis widening in the injured configuration tripled intact ankle syndesmosis widening (2.06 mm vs. 0.97mm, respectively), which compromised the joint stability (Table 3). Any of the proposed fixations importantly reduced the syndesmosis widening. The minimum syndesmosis widening was determined using a single quadricortical screw (0.18mm), whereas the maximum was estimated when using a single suture button with a pretension force of 20N (1.11mm) (Table 3).

		Syndesmosis widening (mm)	Screw/Suture Button Maximum von Mises Stress (MPa)
Intact ankle		0.97	
Injured syndesmosis		2.06	
1 screw	Tricortical	0.91	407
	Quadricortical	0.18	382.6
2 screws	Tricortical: 10 mm distance	0.22	206.2
	Tricortical: 15 mm distance	0.13	336.1
	Tricortical: 18 mm distance	0.32	190.5
	Quadricortical: 10 mm distance	0.68	162.8
	Quadricortical: 15 mm distance	0.69	298.9
	Quadricortical: 18 mm distance	1.02	272.5
1 suture button	Pretension 20N	1.11	11.37
	Pretension 30N	1.10	12.43
	Pretension 40N	1.09	13.49
	Pretension 80N	1.04	17.74
	Pretension 100N	1.01	19.86
2 parallel buttons	Pretension 20N	1.02	11.69
	Pretension 30N	0.99	12.46
	Pretension 40N	0.97	13.25
	Pretension 80N	0.88	16.41
	Pretension 100N	0.83	17.96
2 divergent buttons	Pretension 20N	0.91	9.64
	Pretension 30N	0.90	10.73
	Pretension 40N	0.88	11.83
	Pretension 80N	0.84	16.22
	Pretension 100N	0.81	18.42

Table 3. Syndesmosis widening (mm) and maximum Von Mises stresses (MPa) at the screws/suture buttons for the different configurations simulated.

Several syndesmotic fixations resulted a syndesmosis widening very close to the intact ankle: one single tricortical screw (0.91mm), double quadricortical with 18mm distance (1.02mm), all the fixations using a single suture button, and several fixations with double parallel (20-40N pretension force) and divergent buttons (20-30N pretension force) (Table 3).

Using one single tricortical screw predicted a closer syndesmosis widening (0.91mm) to the intact ankle value (0.97mm) than using one single quadricortical screw (0.18mm). The opposite effect were analysed when double tricortical and quadricortical was analysed. Increasing the distance between the screws increased the syndesmosis widening.

In general, estimation of syndesmotic fixation when using suture buttons showed widening values similar to the ones obtained for the intact ankle. When the pretension increased the syndesmosis widening was reduced. Increasing the number of suture buttons slightly reduced the syndesmosis widening.

3.2.Stress values

Von Mises stresses were higher for the titanium screws than for the suture buttons. The maximum von Mises stress was determined for the single tricortical screw fixation (407MPa). Using double screws reduced the von Mises stresses. The minimum von Mises stress was determined for the double quadricortical with 10mm distance.

For the suture buttons, the von Mises stresses increased when the pretension force increased.

4. Discussion

The main objective of this study was to provide a computational tool to biomechanically compare different syndesmotic fixations. In the literature, there are several finite element analyses of screw fixation for the syndesmotic injuries (Liu et al., 2013, 2016; Serhan et al., 2013; Verim et al., 2014; Serhan et al., 2015). To the best of the authors' knowledge, this is the first publication performing a biomechanical finite element analysis of suture buttons for syndesmotic fixations.

Normally, screw diameters vary between 3.5mm and 4.5mm. Here we only considered a screw diameter of 3.5mm (Thompson and Gesink, 2000; Serhan et al., 2015; Liu et al., 2016). However, there is still no consensus regarding the number of screws, screw diameter or the number of cortices (Liu et al., 2013, 2016; Serhan et al., 2013; Verim et al., 2014; Serhan et al., 2015). Our study showed similar results to previous works, although the numerical results are not comparable due to different patient ankle model, anatomical characteristics, how screws are modeled, and results quantification. Von Mises stress for our titanium screws were between 162.8MPa and 407MPa which were lower than titanium ultimate yield strength (896MPa) (Serham et al., 2015) and very similar to other FE studies (Verim et al., 2014; Serham et al., 2015). Our study estimated a von mises stress of 407MPa using one single tricortical screw, and Serham et al., (2015) obtained a von mises stress of 444.27MPa for the same configuration. Using suture buttons reduces the von mises stresses because of their material properties.

Syndesmotic fixation at the level of 20-40mm above the tibiotalar joint showed enough stability and similar syndesmosis widening to the intact ankle configuration. Verim et al., (2014) compared different positions for a single screw. They concluded that the screw fixation at the level 30-40mm above the tibiotalar joint has advantages compared to other evaluated levels. In our study, we analysed this effect using double screws and similar differences were also estimated (Table 3). One tricortical screw led to a syndesmotic widening comparable to the intact ankle configuration (0.91m vs. 0.97mm, respectively), whereas using a quadricortical screw importantly reduced the syndesmotic widening (0.18mm). Serhan et al. (2012) reported important differences in the behaviour of tricortical and quadricortical fixations when a single screw inclusion was modeled. Our study also supported this conclusion. When using double screws, the sysndesmotic widening reversed its behaviour (Table 3).

Using suture buttons, the syndesmotic widening was closer to the intact ankle configuration (Table 3). In this surgical procedure, a flexible rope is used to substitute the damaged ligament. This flexible rope could have a behaviour similar to the undamaged element. In fact, screw fixation stiffens the tibiofibular joint reducing the syndesmotic widening (Table 3). Using different pretension forces slightly varies the syndesmosis widening (Table 3). To the authors' knowledge, there is no clinical or cadaveric analysis where the effect of the pretension force is studied. Only Westermann et al., (2014) explained how the tension was applied to the suture button construct (82N). Laflamme et al. (2013) reported a better performance of dynamic fixation (suture button) over static fixation (screws) after 12 months follow up. Naqvi et al. (2012) found no significant difference between suture button and screw fixation, but they observed cases of malreduction and risk of suffer it in the future for several patients in the group treated with screw fixation. Neary et al. (2016) included a cost analysis in their study comparing suture button and screw fixations determining the better cost/effective result for suture button when single or double ropes are included versus single or double screws inclusions. Zhang et al. (2017) determined that suture button could lead to better objective range of motion measurements and earlier return to work (Schepers et al., 2018). Raeder et al. (2020) performed a five-year follow-up of patients treated with suture buttons or syndesmotic screws. Their long-term results favoured the use of suture buttons when treating syndesmotic injury. Xie et al. (2018) suggested that suture button fixation could achieve significant higher America Orthopaedic Foot and

Ankle (AOFAS) scores with a lower rate of postoperative complications. In our study, three different configurations using suture buttons were analysed. Increasing the number of suture buttons slightly reduce syndesmotic widening. The divergent technique was the most stable (Table 3) (Parker et al., 2018).

Although the results obtained in this work were quite promising, the computational model was based on several assumptions. Material properties for soft tissues were obtained from the literature (Verim et al., 2014). Cortical thickness was assumed constant and modeled using shell elements. Another related limitation was the assumption of bone tissue as a homogeneous solid with isotropic material properties. The CT scan was not calibrated; therefore, no patient-specific material properties were available. A single model was used to performed this analysis. In the authors' opinions, however, this limitation does not reduce the importance and generality of the obtained results. The evaluation of more patient-specific cases could help to improve the accuracy of the model. This computational model could be validated using previous biomechanical studies with cadaveric specimens (Thompson and Gesink, 2000; Westermann et al., 2014; Clanton et al., 2016).. Only three elements distributed in the upper, middle and lower regions were used to simulate the syndesmosis which is anatomically distributed along the whole bone (Liacouras and Wayne, 2007). A unique loading case was simulated, no other loading cases or cyclic configurations were assumed. Finally, screws were modeled as beam elements neglecting their real geometry, this could affect to their stress distribution.

5. Conclusions

A detailed biomechanical comparison among different syndesmotic fixation was here performed. Screws provided a more rigid syndesmotic fixation than suture buttons. This computational study showed that suture buttons as syndesmotic fixation have advantages with regard to syndesmosis widening in comparison with screw fixation. This could support the good long-term clinical results obtained with dynamic syndesmotic fixation when using suture buttons. Additionally, the computational methodology here proposed could be used as a preoperative planning tool incorporating patient-specific characteristics.

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Conflict of interest

The authors of this manuscript declare that they have no financial and personal relationships with other people or organizations that could inappropriately influence their work.

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