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Biomechanical testing of various suture techniques for Achilles tendon repair with and without augmentation by using synthetic polyester grafts

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ABSTRACT

Following surgical Achilles tendon reconstruction surgery, there is a distinct trend towards an early and faster rehabilitation protocol to avoid muscle atrophy. However, this procedure involves the risk of a higher complication rate. In order to reduce the occurrence of re-ruptures and pathological tendon extensions, a tendon reconstruction with the highest possible primary stability is desirable. Therefore, the aim of this study was to determine if augmentation using synthetic polyester tapes (QuadsTape™) could provide greater primary stability in case of different tendon suture techniques.

90 tendons of the superficial toe flexor of pigs were divided into 9 groups. The reconstruction method was combined using the factors suture technique (Kessler and Bunnell), augmentation (non-augmented and augmented with QuadsTape™) and defect type (end-to-end and 10 mm gap). The biomechanical measurements were performed on a material testing machine and consisted of a creep test, a cyclic test and a tear-off test. This study compared creep strain, ultimate load failure, maximum stress and stiffness.

Irrespective of the type of defect involved, augmentation of the tendon sutures led to a significant increase of the maximum force (not augmented: 82.30 ± 25.48 N, augmented: 135.73 ± 30.69 N, $p < 0.001$) and the maximum stress (not augmented: 2.26 ± 0.83 MPa, augmented: 4.13 ± 1.79 MPa, $p < 0.001$). Furthermore, there was a non-significant increase in stiffness and no significant differences were observed with respect to creep strain.

Augmentation of Achilles tendon reconstruction using QuadsTape™ increases composite strength and stiffness in the *in vitro* model, thus potentially contributing to the feasibility of early rehabilitation programs. Biological factors still need to be investigated in order to formulate appropriate indications.

1. Introduction

Increasing incidence of Achilles tendon ruptures has been observed in recent decades (Huttunen et al., 2014, Lantto et al., 2015, Maffulli et al., 1999, Maffulli, 1999, Sheth et al., 2017). With a percentage of 60–85% (Jozsa et al., 1989, Levi, 1997), sports-related Achilles tendon ruptures are the most prevalent ones in patients between 30 and 45 years of age (Maffulli et al., 1999, Maffulli, 1999, Nyyssönen et al., 2008). However, even for patients in their 60s, spontaneous ruptures increase in frequency as a result of a variety of metabolic or inflammatory conditions (Ames et al., 2008).

Although the rate of rerupture after tendon surgery is relatively low, early exposure and aggressive rehabilitation are associated with an increased risk of rerupture and an increased risk of pathological tendon lengthening. Thus, it has already been proven that divergence of the tendon ends occurs both after early functional mobilization (Mortensen et al., 1999) as well as due to immobilization (Nyström and Holmlund, 1983). This process seems to be able to affect the repair process and lead to known postoperative complications such as plantar flexion weakness or reduced passive stiffness in dorsiflexion (Mullaney et al., 2006). In summary, these studies indicate the need for more stable Achilles repair techniques

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that adequately tolerate an early postoperative rehabilitation program.

At present, there is no uniformly accepted surgical technique for Achilles tendon reconstruction. Almost 60 different methods have been described so far (Crolla et al., 1987), which consider different suture techniques and augmentation methods in combination (Leppilahti and Orava, 1998). *In vivo,* simple adaptation of tendon stumps by end-to-end suture with resorbable material (Guckenberger, 2004) according to Bunnell or Kessler are the most frequently used techniques (Wong et al., 2002) and unofficially represent the standard configuration for surgical Achilles tendon repair (Watson et al., 1995).

For additional augmentation of tendon suture, a variety of different autografts, allografts and xenografts with different mechanical properties are available (Berlet et al., 2014). An increase in the primary stability of the suture by some of these augmentation substances has already been noted in biomechanical studies (Barber et al., 2008), but there is not yet any gold standard. In addition, these materials have the disadvantage of donor morbidity.

There are relatively few research results about the augmentation of Achilles tendon sutures by using synthetic materials. In a biomechanical study, Giza et al. used in human Achilles tendons a synthetic and degradable polyurethane urea which was intended to serve as a scaffold for ingrowth of cells to facilitate healing and stabilize the tendon. In this study, a significantly higher ultimate load failure was recorded in the failure test in comparison with the control group without augmentation (Giza et al., 2011). According to our knowledge, despite the positive results of this study, no further experiments evaluate the biomechanical properties of a tendon augmented with synthetic material in comparison with non-augmented tendons.

We have hypothesized that augmentation of tendon suture using synthetic polyester tapes (QuadsTape™) compared to suture-only, will increase primary stability in the *in vitro* model and allow for less loss of strength of the tendon reconstruction thanks to increased stiffness values. In addition, it was to be determined in combination with which suture technique (Bunnell or Kessler) and depending on the type of defect involved, the most favorable biomechanical properties can be obtained.

2. Material and methods

Due to anatomical and physiological properties similar to human tendons (Mao et al., 2011), the tendons of the M. flexor digitorum superficialis (superficial toe flexor) of the pig were selected for this study (Zatiti et al., 1998, Oswald et al., 2017). The tendons of the M. flexorum digitorum superficialis were separated from 90 fore feet of pigs, their soft tissue was removed and they were checked for any macroscopic deficiencies. The tendons then were frozen at −20 °C and thawed for testing for 30 min in 37 °C warm NaCl solution. Oswald et al. recommend the applied cryopreservation for scientific studies of mechanical properties of tendons (Oswald et al., 2017). Subsequently, the tendons were randomly distributed among 9 groups, with the suture techniques, augmentation methods and the distance of the ruptured tendon ends varying within these groups (Table 1).

Before carrying out the load tests, the tendons were uniaxially clamped into a compression-tension testing machine (Inspekt table Blue 20 EDC 222, Hegewald & Peschke Meß- und Prüftechnik GmbH, Nossen, Germany), preloaded with a tensile force of 10 N – analogous to Clavert et al. and Oswald et al. (Clavert et al., 2001, Oswald et al., 2017), and at four defined measurement points the diameter was measured by laser at the point of least circumference (Fig. 1). Thus, the cross-section could be approximately reconstructed and calculated. Subsequently, a defect was provided by means of a scalpel and the tendons were reconstructed in a group-dependent manner under a standardized stress (Fig. 2).

2.1. Augmentation

Augmentation was performed using a 30 mm wide QuadsTape™ system (Neoligaments™, A division of Xiros™, Springfield House, Whitehouse Lane, Leeds LS19 7UE UK) (Fig. 3). These are sterile, non-absorbable polyester tapes that cause a minor inflammatory response in the tissue and are subsequently fibrously encapsulated. According to the manufacturer, indication for the application is, among other things, the reconstruction of damaged or torn ligaments and tendons. For tendon augmentation, the QuadsTape™ is designed to integrate well into the patient's tissue and serve as a scaffold for ingrowth of cells (neoligaments™).

The QuadsTape™ was fixed to the tendon by using absorbable polyglactin 910 sutures (Vicryl™ Plus 3-0, Johnson & Johnson Medical GmbH, Norderstedt).

2.2. Suture technique

In this study, the two suturing techniques to Bunnell and Kessler (Wong et al., 2002) were used which are most commonly applied *in vivo* (Fig. 4). The interlacing length was chosen based on the complexity of the particular suture technique by an experienced surgeon. Therefore, the longer interlacing of the Bunnell suture only results from the higher number of loops. Both sutures were performed with resorbable polydioxanone (PDS™ II, Johnson & Johnson Medical GmbH, Norderstedt).

2.3. Type of defect

Since it is quite common in practice that due to a possible retraction of the tendon ends after a chronic rupture, these cannot be treated end-to-end, in this study we also examined the influence of an approx. 10 mm large gap on the primary stability of tendon repair. In clinical practice, we have often been able to observe an in situ gap despite maximal plantar flexion of the foot. Due to this or in case of this incomplete this incomplete approach, a 10 mm dehiscence was chosen as a defect. Therefore, the 10 mm gap was left prior to the suture in groups 6–9.

After group-dependent reconstruction of the tendons they were clamped into the material testing machine (Fig. 5) and subjected to a creep test, a cyclic test and a tear-off test with intermittent 30-minute pauses. In order to determine the creep behavior in the creep test at a constant feed speed of 5 N/s, the load of the tendons was set to 30 N and held for 15 min. In the subsequent cyclic test, analogous to Barber et al. and Giza et al., the lower load limit was at 2 N and the upper load limit at 30 N (Barber et al., 2008; Giza et al., 2011). A total of 500 cycles were performed at a frequency of 0.4 Hz. In the tear-off test, the tendons were loaded to failure at a feed speed of 300 N/s. Each time before and after a test, there was a 90-second pre-load phase at 10 N.

The statistical evaluation of the results was done with SPSS 22.0.1 (Version for Windows, Evaluation Version, IBM, Armonk, NY, USA). Only those parameters were used for more detailed evaluation, which have the greatest significance for estimating the primary stability of the Achilles tendon reconstructions. Both the creep test and the cyclic test evaluated the influence of suture technique, augmentation and defect type on the creep strain in %. The tear-off test evaluated the influence of suture technique, augmentation and defect type on the maximum force in N, the maximum stress in N/mm^2 and the stiffness in N/mm. Using the Shapiro-Wilk test, the data were tested for normal distribution by means of a 95% confidence interval of the mean values. Based on the actual variance heterogeneity of the mean values, a

Table 1
Tabular overview of the group classification.

Group	n (sample size)	Suture technique	Augmentation	Defect
1	10	native	–	–
2	10	Kessler	–	end-to-end
3	10	Kessler	QuadsTape™	end-to-end
4	10	Bunnell	–	end-to-end
5	10	Bunnell	QuadsTape™	end-to-end
6	10	Kessler	–	gap
7	10	Kessler	QuadsTape™	gap
8	10	Bunnell	–	gap
9	10	Bunnell	QuadsTape™	gap

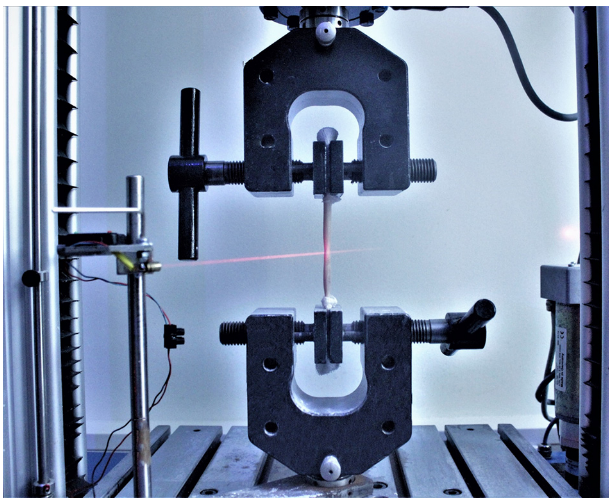

Fig. 1. Assembly of the material testing machine for cross-section measurement.

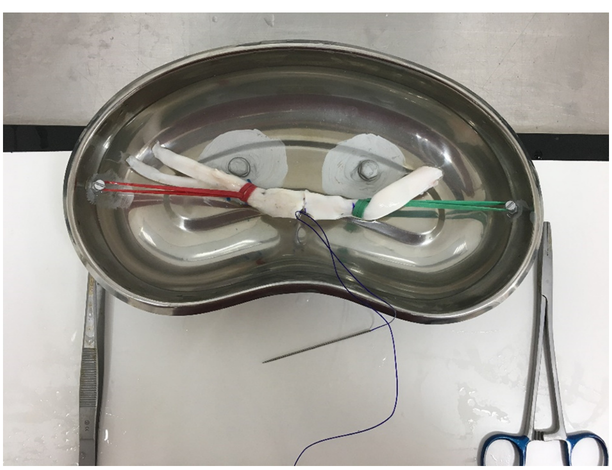

Fig. 2. To reconstruct cross area section of the tendons under a standardized tension, they were fixed 3 cm to the left and right of the defect in a kidney dish using rubber bands.

Fig. 3. QuadsTape™ mesh made of polyester with a width of 30 mm. The double mesh structure ensures high strength.

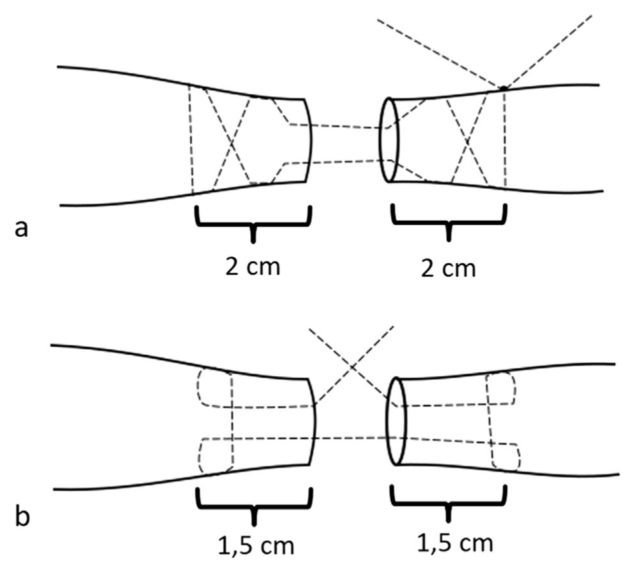

Fig. 4. (a) Suture technique according to Bunnell. (b) Suture technique according to Kessler.

Kruskal-Wallis test was carried out to evaluate the differences between the groups. In order to control the multiple testing and to further investigate between which groups there are differences, pairwise comparisons were made with a Dunn-Bonferroni test. The global significance level was set to $p < 0.05$. Subsequently, an exploratory data analysis and a direct comparison of the mean values were used to determine how great the difference actually was, in order to be able to assess whether, in addition to a possible statistical significance, there was also a clinical significance.

3. Results

3.1. Creep test

There were no significant differences in creep strain as a function of augmentation (without QuadsTape™ 2.07 ± 0.49% vs QuadsTape™ 2.12 ± 0.38%, $p > 0.05$). When comparing the suturing techniques, the creep strain of the tendons reconstructed with Kessler suture was on average significantly lower than the creep strain of the Bunnell suture tendons (1.86 ± 0.24% vs. 2.33 ± 0.46%; $p < 0.001$). The creep strain of the end-to-end adapted tendons was 2.11 ± 0.44%, which was not significantly

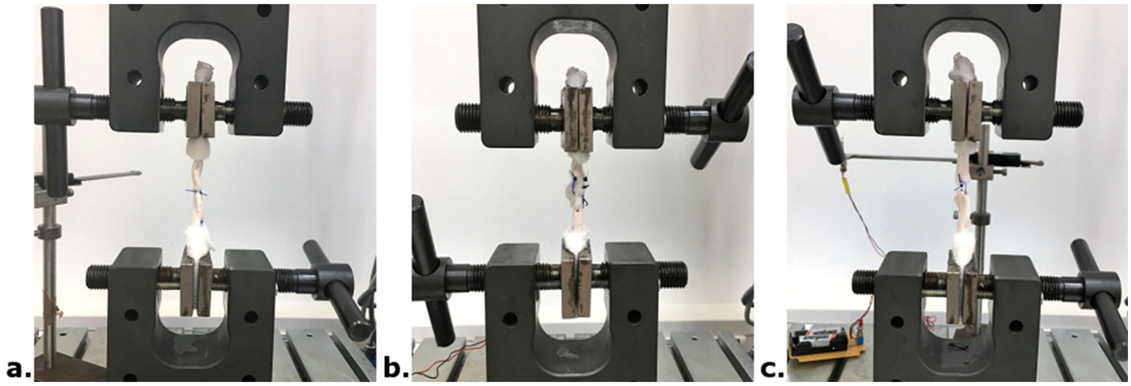

Fig. 5. After group-specific reconstruction, the tendons were uniaxially clamped in the material testing machine. (a) – End-to-End Kessler Suture (b) – Bunnell Suture with QuadsTape™ (c) – Kessler Suture with Gap.

different from that of the Gap tendons (2.08 ± 0.43%). No gap formation was observed.

3.2. Cyclic test

The cyclic test also showed no significant difference between the tendons without QuadsTape™ (2.84 ± 1.11%) and the tendons with QuadsTape™ (2.49 ± 0.84%). When comparing the sutures, the Kessler group showed significantly lower values, i.e. 2.10 ± 0.61%, than the Bunnell group with 2.10 ± 0.61% ($p < 0.001$). The creep strain averages across the groups of different defect types, i.e. end-to-end defect type (2.83 ± 1.14%) and Gap type (2.50 ± 0.79%) were not significantly different. Again, no gap formation could be observed.

3.3. Tear-off test

The ultimate load failure of tendons augmented with QuadsTape™ was significantly greater than that of non-augmented tendons (135.73 ± 30.69 N vs. 82.30 ± 25.48 N, $p < 0.001$). The augmented tendons also showed significantly higher values for maximum stress and stiffness (Table 2). Comparing the mean values of the maximum forces depending on the suture technique, no significant differences could be found between Kessler (115.85 ± 39.35 N) and Bunnell (102.19 ± 37.56 N). However, the tendons reconstructed by using the Bunnell technique showed a maximum stress of 4.19 ± 1.62 N/mm^2. These were significantly higher values compared to Kessler with 2.20 ± 1.01 N/mm^2 ($p < 0.001$). The situation was similar for the stiffness values. Bunnell (10.93 ± 5.18 N/mm) showed significantly higher stiffness than Kessler (6.20 ± 4.64 N/mm). As far as defect types are concerned, no significant differences could be found between an end-to-end suture and a suture with gap in terms of ultimate load failure, maximum stress and stiffness.

The results of the pair-by-pair group comparisons for the parameters tested in the tear-off test including the statistical differences between groups with $p < 0.05$ are shown in Table 3. In all parameters examined, the values of the native control group differed many times more significantly from those tendons with defects. The results were graphically presented without the native group in order to focus on the comparison of the reconstruction modes of the tendon (Fig. 6).

Table 2
Significance of the measured value comparisons of the means of maximum force, maximum tension, and rigidity over the augmentation in the tearing test.

	Not augmented MV ± SD	Augmented MV ± SD	p value
Ultimate load failure [N]	82.30 ± 25.48	135.73 ± 30.69	p < 0.001
Max stress [N/mm^2]	2.26 ± 0.83	4.13 ± 1.79	p = 0.001
Stiffness [N/mm]	7.25 ± 4.29	9.88 ± 6.15	–

Regarding the ultimate load strength, there is a clear gap between augmented and non-augmented groups. By placing the maximum force in relation to the tendon cross-section, the tendons reconstructed in a combination of QuadsTape™ and Bunnell suture stand out particularly. The maximum stresses of these two groups (5.44 ± 0.85 MPa and 5.75 ± 1.12 MPa, respectively) were up to 200% of the values of the other groups. It also becomes evident that the mean stiffness value of the augmented and Bunnell-sutured tendons (groups 5 and 9) with the values of 16.43 ± 6.10 N/mm and 11.83 ± 2.12 N/mm, respectively, clearly exceeds the values of the other groups.

4. Discussion

After surgical treatment of Achilles tendon rupture, there is a clear trend towards an early rehabilitation protocol, as early tensile loads improve the mechanical properties of the Achilles tendon (Schepull and Aspenberg, 2013). Although the rate of re-rupture after surgery is relatively low, early loading and rapid rehabilitation go hand in hand with an increased risk of re-rupture, pathological tendon lengthening (Mortensen et al., 1999), plantar flexion weakness, or decreased passive stiffness during dorsal extension (Mullaney et al., 2006). Thus, primary stability of the Achilles tendon repair is the primary goal of surgical reconstruction and the deciding factor for surgical success (Sadoghi et al., 2012).

This study compares the mechanical properties of Bunnell or Kessler reconstructed pig's Achilles tendons augmented by means of synthetic polyester tapes (QuadsTape™) with tendons which were not augmented. Moreover, the investigation was to show whether the result depended on the type of defect (end-to-end and "gap").

4.1. Augmentation

The use of QuadsTape™ as augmentation material initially did not significantly reduce creep strain, neither in the creep nor in the cyclic test. Thus, during constant and cyclic loading at 30 N no influence on defect enlargement nor on possible pathological tendon lengthening could be determined. However, the augmentation had an influence on the maximum force and the maximum strain determined in the tear-off test. Thus, statistically the maximum force could be significantly increased to 135.73 ± 30.69 N ($p < 0.001$) compared to non-augmented and suture-only constructions of 82.30 ± 25.48 N, which constituted an increase of 65%.

Table 3
Significance of the measurement comparisons of the means of maximum force, maximum stress, and stiffness across all groups. The p-values of the pairwise comparisons are indicated by the indicia.

	Control group	End-to-end				Gap				p value
	Native	Kessler		Bunnell		Kessler		Bunnell		
		Non-augmented	Augmented	Non-augmented	Augmented	Non-augmented	Augmented	Non-augmented	Augmented	
	1	2	3	4	5	6	7	8	9	
	MV ± SD	MV ± SD	MV ± SD	MV ± SD	MV ± SD	MV ± SD	MV ± SD	MV ± SD	MV ± SD	
Ultimate failure load [N]	1580.07 ± 301.69^{a,b,c,d}	85.66 ± 31.05^{a}	135.28 ± 42.40^{e}	75.71 ± 14.55^{b,f,g}	138.47 ± 26.26^{f,h}	102.22 ± 25.26^{c}	140.42 ± 31.79^{g,i}	65.63 ± 13.72^{d,e,h,i,j}	128.93 ± 22.41^{j}	a < 0.001; b < 0.001; c = 0.004; d < 0.001; e = 0.012; f = 0.020; g = 0.018; h = 0.003; i = 0.003; j = 0.020
Max stress [N/mm^2]	65.03 ± 13.27^{a,b,c,d,e}	1.59 ± 0.68^{a,f,g}	2.69 ± 1.19^{b}	2.99 ± 0.55	5.44 ± 0.85^{f,h}	1.89 ± 0.82^{c,h,i}	2.64 ± 0.94^{d}	2.58 ± 0.41^{e}	5.75 ± 1.12^{g,i}	a < 0.001; b = 0.004; c < 0.001; d = 0.003; e = 0.005; f < 0.001; g < 0.001; h < 0.001; i < 0.001;
Stiffness [N/mm]	183.97 ± 61.91^{a,b,c,d,e}	8.86 ± 6.58^{a}	5.97 ± 5.32^{b,f,g}	8.02 ± 1.88	11.83 ± 2.12^{f,h}	4.67 ± 2.92^{c,h,i}	5.31 ± 1.30^{d,j}	7.46 ± 3.69^{e}	16.43 ± 6.10^{g,i,j}	a = 0.005; b < 0.001; c < 0.001; d < 0.001; e = 0.007; f = 0.028; g = 0.003; h = 0.004; i < 0.001; j = 0.010

Likewise, the maximum stress was increased by about 83% (non-augmented: 2.26 ± 0.83 MPa, augmented: 4.13 ± 1.79 MPa, p = 0.001). In terms of stiffness, too, the tendon ends augmented by QuadsTape™ are superior, but don't show any significant difference. A lack of significance is most likely explained by the high standard deviations of the groups (non-augmented: 7.25 ± 4.29 N/mm, augmented: 9.88 ± 6.15 N/mm). These results indicate a major mechanical advantage of augmented tendons compared to non-augmented tendons. The results obtained in the tear-off test thus confirm the results of other authors. Giza et al., who also use synthetic augmentation (Giza et al., 2011). Comparing the results with studies using xenografts for additional suture augmentation on human Achilles tendons gives similar results. Both Berlet et al. as well as Wisbeck et al. Thus, failure-induced ultimate load failure and stiffness tests (Berlet et al., 2014, Wisbeck et al., 2012). However, a comparison of the absolute values with those found in literature is rather difficult due to differing tendon material and experimental protocols. Thus, with respect to the maximum-load augmented tendons, a biomechanical advantage can be attributed compared to non-augmented tendons and thus potentially a reduction in re-rupture rates can be achieved. For a potential clinical use, however, these results must be critically evaluated, as the re-ruptures are not the major complication despite aggressive rehabilitation protocols. The main problem of pathological tendon extensions (Wong et al. 2002) would not be resolved by augmentation, as creeping and cyclic tests showed no reduction in tendon stretching.

4.2. Suture technique

In current literature, Bunnell technique is associated with higher primary stability. However, these statements were made only on the basis of failure tests (Herbort et al., 2008, Sadoghi et al., 2012). Considering the creep strain, higher values in the creep and cyclic tests were found in this study for the Bunnell suture compared to the Kessler suture, which is an indication of lower primary stability and a tendency for pathological tendon lengthening. We presume that this is due to the higher number of knots of the Bunnell suture (Fig. 4). This provides a little more clearance for the Bunnel suture thread until it is finally anchored in a fixed position in the tendon material. Thus, it may be assumed that the tensile forces in the creep test and in the cyclic test precisely made use of this clearance until the thread was finally blocked in the tendon. Therefore, the higher values would not be interpreted as lower primary stability. Rather, this process is a prerequisite for increasing the bond strength of the reconstruction, as it could also be shown in the tear-off test. Comparing accordingly the stiffness of both techniques, Bunnell sutures could slightly reduce the loss of strength of tendon reconstruction (Bunnell: 10.93 ± 5.18 N/mm, Kessler: 6.20 ± 4.64 N/mm) as it has already been shown by Herbort et al. (Herbort et al., 2008). Results contrary to the current state of research arise when comparing in this study the ultimate load failure of the mere Kessler suture with the mere Bunnell suture. While in literature there is large tendency towards attesting a greater maximum force to the Bunnell suture, in this study the Kessler suture-only is attested a higher maximal force (85.66–102.22 N vs. 65.63–75.71 N). However, setting the maximum force in relation to the tendon cross-section and considering the maximum stress, higher values can be obtained by using the mere Bunnell suture (2.58 ± 0.41–2.99 ± 0.55 N/mm^2) than by using the Kessler suture-only (1.59 ± 0.68–1.89 ± 0.82 N/mm^2). Thus, despite the randomized allocation, the considerably lower average cross section of the tendons used for Bunnell groups compared to those for the Kessler groups could be the cause of the lower maximum force.

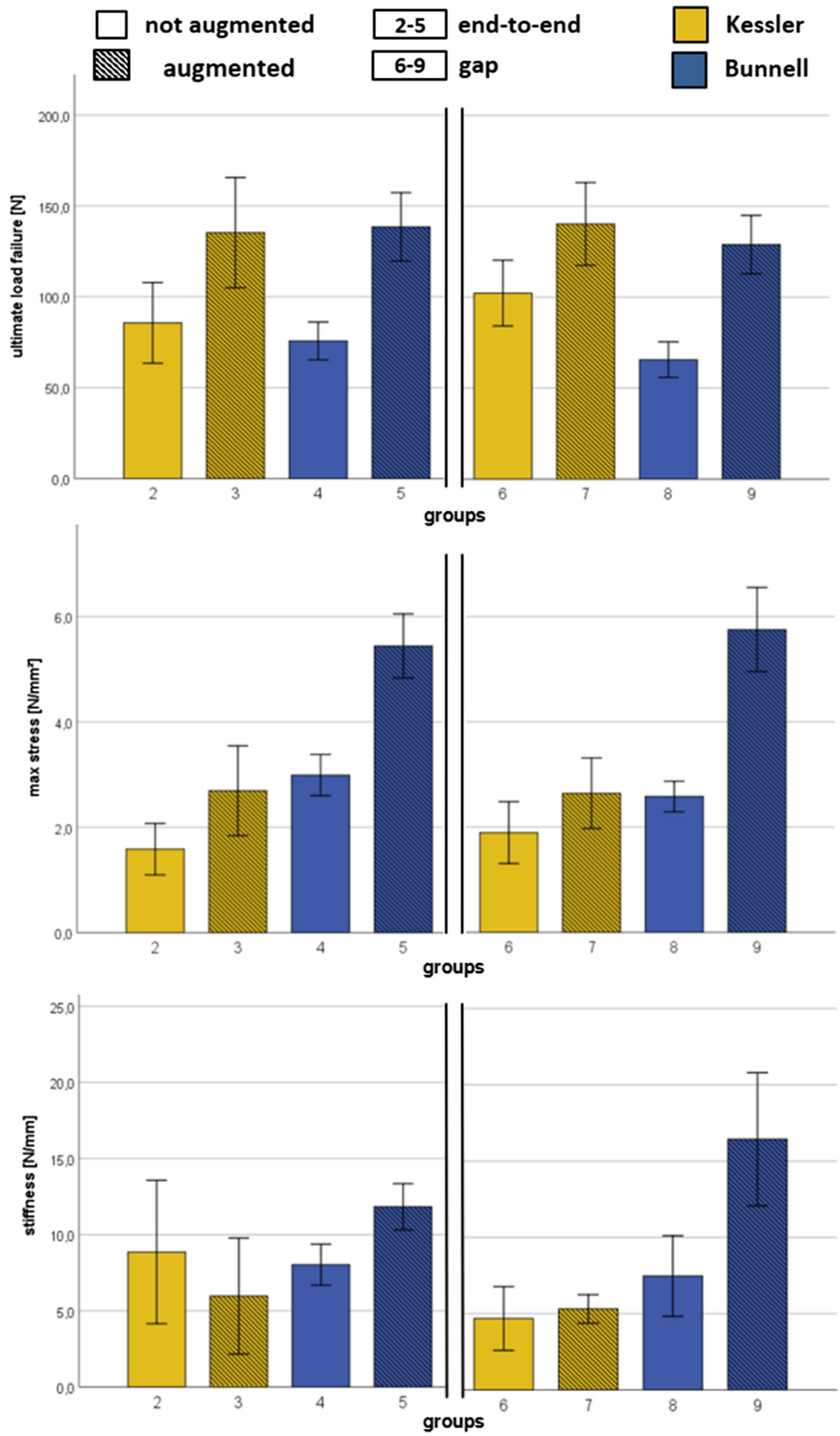

Fig. 6. Average comparison of the maximum force, maximum tension, stiffness in the tear test via the groups 2–9.

4.3. Type of defect

In a comparison among all groups, no significant difference was found in any of the three tests and for any of the parameters studied. Accordingly, it can be concluded that the type of defect postoperatively has no influence on the primary stability of tendon reconstruction. In comparable biomechanical studies either end-to-end was used or the type of defect was not specified, so that no comparison is possible. Despite the lack of difference as far as the type of defect is involved, in practice it is more advisable to perform an end-to-end suture, as this will allow the tendon ends to be more precisely adapted and to achieve continuity earlier, irrespective of the suturing technique.

4.4. Pairwise group comparison

A comparison of the groups with each other provided information on the most efficient combination of augmentation method, suture technique and type of defect in terms of primary stability. In the tear-off test, considering maximum stress and stiffness, the Bunnell sutures augmented with QuadsTape™, irrespective of the type of defect, appear to have the most favorable effect on primary stability (Groups 5 and 9). Compared to tendon ruptures (groups 3 and 7) treated with Kessler suture and QuadsTape™ augmentation, the stress of these groups is approximately twice as high (5.44–5.75 MPa vs. 2.64–2.69 MPa; $p < 0.001$). Also regarding stiffness, the tendons provided with QuadsTape™ and Bunnell show significantly higher values than the tendons treated with QuadsTape™ and Kessler (11.83–16.43 N/mm vs. 5.31–5.97 N/mm, $p < 0.05$). Only when comparing the ultimate load failure, the values are almost identical (128.93–138.47 N vs. 135.28–140.42 N), which fact in turn might be attributed to the smaller cross-sectional tendons of the Bunnell group.

4.5. Limitations

It must be emphasized that this study can only assess the mechanical behavior of the sutures *in vitro*. Biological factors and potential adverse reactions associated with using QuadsTape™ during the healing process remain to be investigated. Furthermore, it is a simplified model that cannot really represent the *in vivo* conditions. This means that additional limitations of this study have to be considered. First of all, we have to take into account the way the defect is provided. In this model, clean cuts were made on optically healthy tendons, while clinical ruptures are more complex and often a combination of achillo tendinopathy and trauma, and are rarely caused by laceration (MacLean et al., 2012, Maffulli et al., 2011). In this respect, the absolute values obtained in this study may overestimate the actual primary stability of tendon reconstruction. In addition, the defect was apparently placed at the narrowest point of the tendon, as it was assumed that at this place there would be the highest risk of rupture under load. However, rupture localization *in vivo* also critically depends on the blood supply within a tendon area (Chen et al., 2009), which may vary interindividually (Paar et al., 2001), so that the precise place where a defect is provided might not correspond with certainty to a defect which may occur clinically. Moreover, although having properties similar to human tendons (Mao et al., 2011), the Achilles tendons of pigs which were used do not allow a final statement concerning human tendons. Besides, the forces used in the creep and cyclic tests could be significantly different from the actual forces encountered in postoperative rehabilitation. Finally, there are no standardized experimental protocols in literature, which makes it more difficult to compare with the results of other studies.

5. Conclusion

In this biomechanical model, Quads Tape™ augmented tendon reconstructions showed higher stiffness and significantly higher ultimate load failure and maximum stress compared to the non-augmented group. However, neither in the creep test nor in the cyclic test, any influence of an augmentation on a pathological tendon prolongation could be detected. Thus, from a clinical point of view, our investigations show that the use of synthetic augmentation to reduce pathological tendon lengthening would not be worthwhile as the increased costs are unlikely to result in a decreased complication rate. However, patients with increased risk of re-rupture due to high postoperative tractive efforts may benefit from augmentation. Also patients with existing degeneration of the tendon, who should get higher primary stability, possibly in order to avoid tearing-off or dehiscence in case of flush suture and poor tendon material, could benefit in this case. Further research is needed to formulate detailed indications for using QuadsTape™. It is recommended to perform a tendon suture with the Bunnell technique irrespective of the type of defect since this suturing technique has the most favorable influence on the primary stability and came closest to the values of the native control group.

Author contributions

All authors have made substantial contributions to all of the following: (1) conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted.

Declaration of Competing Interest

In the name of the authors of the manuscript "Biomechanical testing of various suture techniques for Achilles tendon repair with and without augmentation by using synthetic polyester grafts", I declare that the material therein has not been and will not be submitted for publication elsewhere except as an abstract, authors do not have any commercial relationship that might lead to a conflict of interests, and finally, all authors were fully involved in the study and preparation of the manuscript and each of the authors has read and concurs with the content in the final manuscript.

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