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Long term evolution of soft tissue response in the fingers of high-level sport climbers: A cross-sectional 10 Year follow-up study

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A B S T R A C T

Background: Sport climbing induces physiological changes in the body of high-level climbers. In 2012, our study group demonstrated adaptions of elite climbers' soft tissues with thicker A2/A4-pulleys, flexor tendons and palmar plates compared to non-climbers.
Objectives: To assess these adaptations over time we examined all 31 (follow up 100%) climbers that participated in that baseline study again using ultrasonography after a follow-up of 10 years.
Main findings: (1) In climbers, a significant increase in A2 and A4-pulley and flexor tendon thickness over the last 10 years was observed ($p < 0.001$), while PIP&DIP palmar plate thickness remained unchanged ($p > 0.05$); (2) at 10-years follow-up, all soft tissue thickness parameters (incl. palmar plates) were still significantly larger in climbers than in age-matched controls ($p < 0.05$); (3) as for the association with anthropometrics and climbing performance/experience, a significant association of the current climber's soft tissue thickness could only be found between palmar plate and reached climbing level($p = 0.032$) as well as climber's body weight($p = 0.004$).
Conclusion: An accumulation of repetitive climbing-related stress to the fingers of elite sport climbers over the career induces mechano-adaptation of the A2/A4-pulleys, flexor tendons and palmar plates. At later stages, there is a further significant increase in flexor tendon and pulley thickness, but not for palmar plate thickness.

1. Introduction

Sport climbing continues to be a popular and fast-growing sport, recently included in the Olympic program for the Tokyo Summer Games. In the past a steep evolution of this sport with increased availability of climbing routes, better equipment and training facilities already took place (Schweizer, 2012). This recent boost of popularity is likely to have influenced this development even more and will further encourage more athletes to participate in this sport earlier in life and on a higher level (Schoffl et al., 2018a). With newer training methods and financial support athletes nowadays are reaching higher difficulty levels and, therefore, are adding more climbing years to their bodies. Today the highest climbing level is 9c on the French scale, with a high probability that the recent development will push this limit further upwards.

During climbing, the entire weight of the climber must be held with sometimes only one finger, applying extreme forces to the connective tissues (Moor et al., 2009). The focus of climbing-related research has so far been mainly on acute climbing injuries and performance, neglecting the long-term effects to the human body after intensive climbing. Ten years ago, our study group investigated the influence of high mechanical stress from climbing on the fingers of 31 elite level sport climbers and demonstrated adaptations in connective tissues with thicker pulleys, palmar plates and flexor tendons compared to a non-climbing controls (Schreiber et al., 2015). However, a potential correlation between lifelong climbing-related stress on the fingers, body weight, maximal

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climbing levels reached and its consequence on the soft tissues could not be investigated at that time.

Therefore, the aims of this study were: (1) to sonographically assess the thickness changes of the flexor tendons, A2/A4 pulleys and PIP/DIP palmar plates in the fingers of elite sport climbers with a minimum 25 years of climbing history over the last 10-year time frame, (2) to compare these soft tissue thickness measures between elite sport climbers at the 10-year follow-up with that of age-matched non-climbing controls, and (3) to evaluate the association of the climbers' current tendon, pulley and palmar plate thickness with body weight, years of climbing, and maximally reached climbing level.

2. Material and methods

2.1. Participants and study design

Ten years after our baseline study on "Connective tissue adaptations in the fingers of performance sport climbers"(Schreiber et al., 2015), all 31 elite rock-climbers were invited for a follow-up investigation. At follow-up climbers were aged in average 48.3 ± 5.0 years. Besides participation in the baseline study the inclusion criteria were being an elite level rock climber with a minimum level of 7b+ on the French scale and minimum of 25 climbing years. Exclusion criteria were quitting climbing activities, major operations or injuries to the hands or rejected informed consent. None of the climbers had to be excluded. All participants were contacted by telephone over a time-period from April to August 2019 and could be examined exactly 10 years after the baseline study (follow-up rate 100%).

Unfortunately, the control group that was studied 10 years ago was not available for another examination, therefore, 15 new non-climbing participants served as age- and gender-matched controls. Controls were aged 48.1 ± 6.1 years in average. Most of them were employers from different occupational fields of our University Hospital. Non-participation in climbing or climbing-related training were the inclusion criteria for the control group. Exclusion criteria were the same as for the climbing group, as well as pain, major injuries or operations in their fingers. This study was approved by the local ethics committee (Cantonal Ethics Commission Zurich, Switzerland, BASEC-Nr. 2019-00677), and all participants signed a written informed consent.

2.2. Data collection and evaluation

Ultrasonography examinations were performed by either author 2 (A.S.) or author 3 (L.R.). Due to the small elite climbers' community, it was not possible to blind the examiners to the climber's status. Furthermore, hands of elite climbers are visually easy to recognize by thicker joints and bruises. In accordance to Schreiber et al. (Schreiber et al., 2015), we used an ultrasound device (Medison HM70A with a 15 MHz hockey stick probe LS 6 and a linear field of view) and the same measuring principles. Every digit of both hands except the thumb were examined at the proximal and middle phalanx. A minimum of compression was applied in all investigations and ultrasound gel was used to improve image quality. All pictures were stored, and the below aforementioned structures were measured post-hoc by means of the software

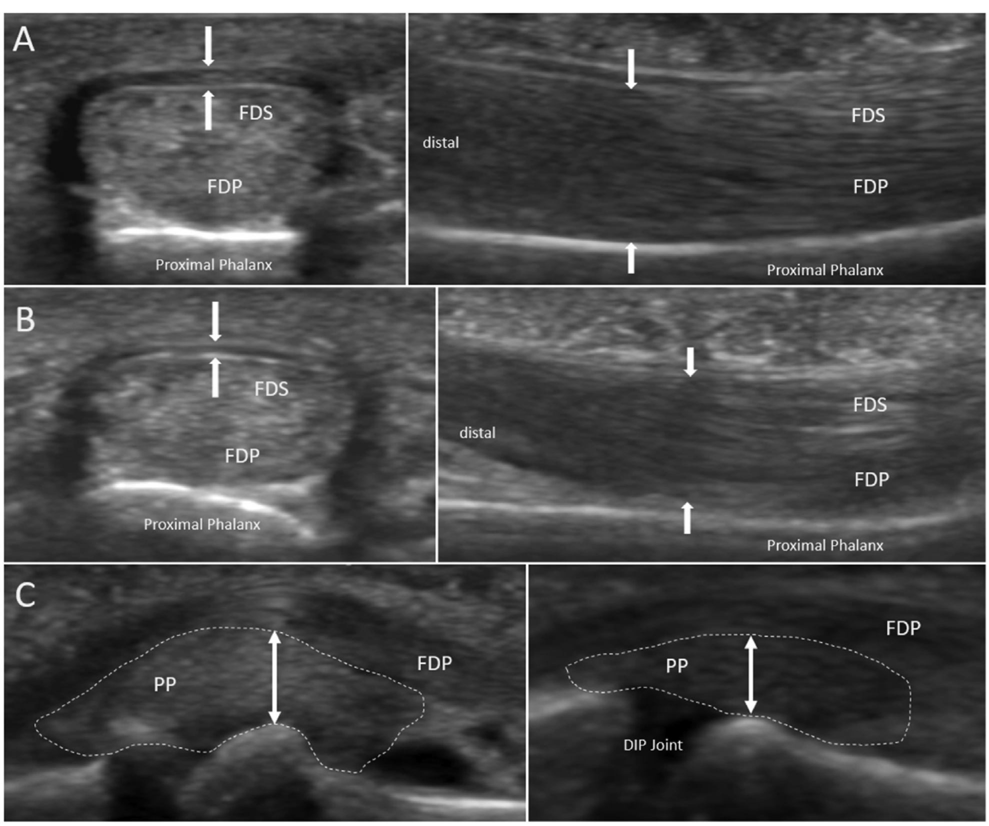

Fig. 1. Ultrasound examination. **A**: Left: axial view of a climber's A2 pulley (between white arrows). Right: axial view of climber's flexor tendons at their stoutest point under the A2 pulley. Measurement points for A2 pulley thickness were set at the tip of both arrows (left). Flexor tendons were measured between white arrows (right). **B:** Same view as displayed in A in a non-climber. Note the thinner A2 pulley and flexor tendons. **C:** Left: Sagittal view of a climber's palmar plate (marked with dotted line) of a DIP joint. Points of measurements were set at the tip of the white arrows. Right: same view in a non-climber. Note the thicker palmar plate in the climber.

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implemented on the ultrasound device by the last author (T.P.) The thickness of the A2 and A4 pulleys was measured in the axial plane at the most distinct and stout location of the pulley. The flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) tendons were visualized at their thickest point and measured combined in the sagittal plane at the level directly below the A2 and A4 pulley. The palmar plate (PP) was only displayed in the sagittal plane and thickness was measured at the proximal interphalangeal joint (PIP) and distal interphalangeal joint (DIP) between the highest part of the distal middle phalanx and the most convex part of the flexor tendons. All measurement principles used are illustrated in Fig. 1. Subsequently, all values were compared to the baseline data collected by our study group 10 years ago. In addition, data on participants' anthropometry and climbing history were collected by means of a questionnaire and were compared to the baseline study 10 years ago.

2.3. Statistical analysis

The following steps of statistical analysis were performed: (1) all anthropometric and climbing-related measures were reported as mean, SD, median and range; (2) potential tendon, pulley, and palmar plate thickness differences were assessed by repeated-measures multivariate ANOVA ($p < 0.05$) with Bonferroni Correction for pairwise comparisons. Within-subject factors were digit (Dig II-V) and side (right and left), between-subject factor was the group (climbers at baseline, climbers at 10-years follow-up, and age-matched controls); (2) for each parameter, digit and side detailed group differences were analysed by unpaired sample t-tests ($p < 0.05$). Additionally, detailed group comparisons were graphically illustrated by mean and 95%CI plots; and (3) for evaluating the association of the current tendon, pulley and palmar plate thickness with the climbers' body weight, years of climbing, and maximally reached climbing level, multiple regression models were used ($p < 0.05$).

3. Results

3.1. Baseline characteristics of the participants

The average climbing level of the climbers' group was 7c+ on the French scale (range 7b+ to 9a+). Average boulder level was 7c+ (range 7a to 8c+). Their average climbing career start was at 15.4 ± 3.3 y (range 6.0 and 24.0 y) and overall average climbing time was 31.6 ± 4.4 y (range 25.0–42.0 y). Mean body weight was 72.8 ± 7.2 kg (range 54.0–92.0 kg) and mean body height was 1.78 ± 0.04 m (range 1.67–1.86 m).

3.2. Differences in soft tissue thickness

Multivariate tests revealed significant differences between the groups ($p < 0.001$; partial eta2 = 0.541) and digits ($p < 0.001$; partial eta2 = 0.941) but not between the sides ($p = 0.119$; partial eta2 = 0.149). Interaction effects were observed for digit*side

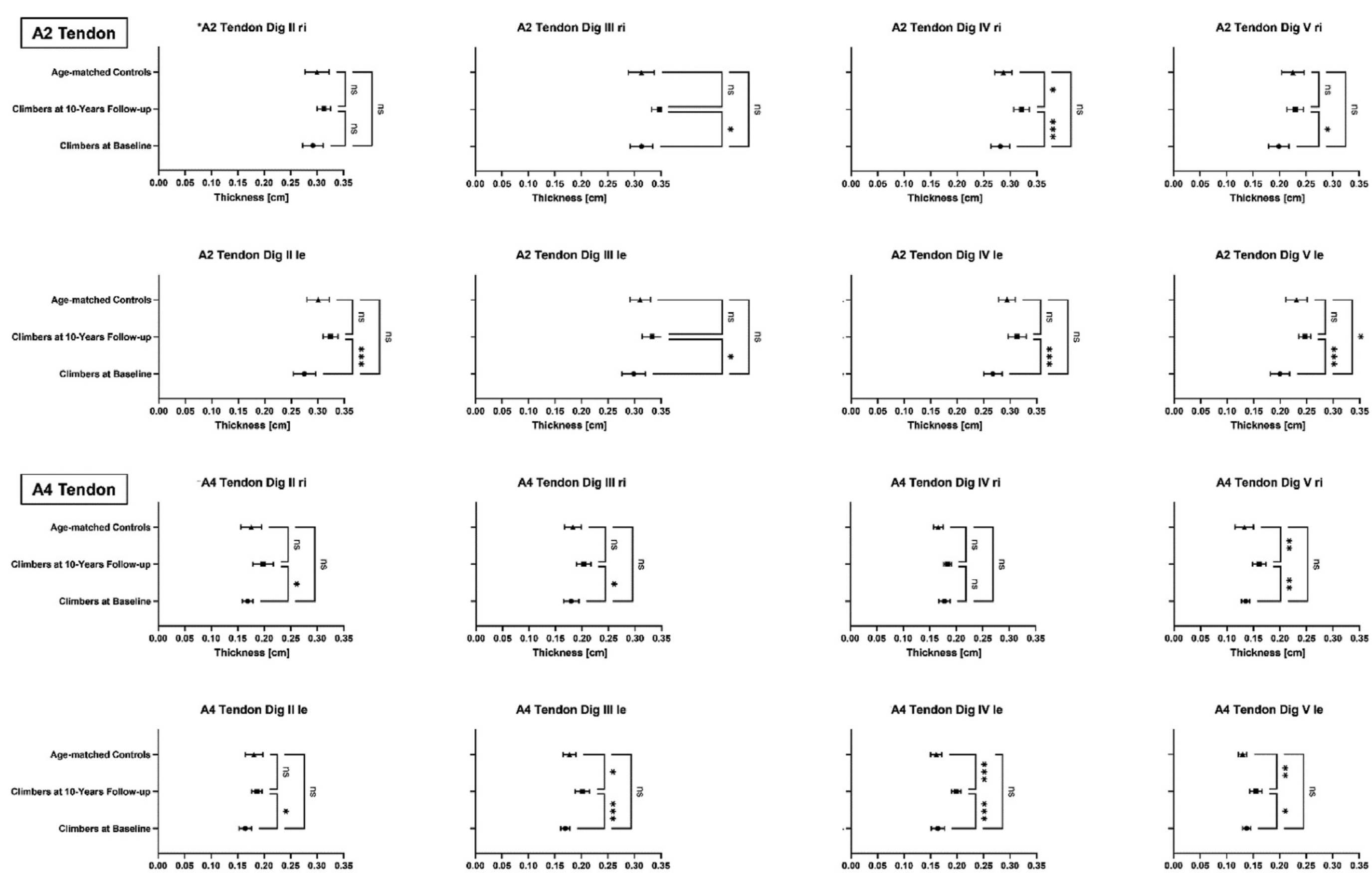

Fig. 2. Descriptive and inferential statistics digit- and side dependent A2 and A4 tendon thickness between the groups of climbers at baseline, climbers at 10 years follow-up and age-matched controls.
Level of significance based on unpaired sample t-tests: ns, not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. PIP: proximal interphalangeal joint; DIP: distal interphalangeal joint; Dig: digitorum; le:left; ri: right.

($p = 0.044$; partial eta2 = 0.406), but not for digit*group ($p = 0.081$; partial eta2 = 0.346), side*group ($p = 0.976$; partial eta2 = 0.034), and digit*side*group ($p = 0.125$; partial eta2 = 0.332). Univariate tests with respect to group differences showed significant results for all soft tissue thickness parameters assessed (A2 tendon: $p < 0.001$, partial eta2 = 0.324; A2 pulley: $p < 0.001$, partial eta2 = 0.421; PIP palmar plate: $p = 0.001$, partial eta2 = 0.197; A4 tendon: $p < 0.001$, partial eta2 = 0.404; A4 pulley: $p < 0.001$, partial eta2 = 0.413; DIP palmar plate: $p = 0.001$, partial eta2 = 0.513). In climbers, pairwise comparisons indicated significant increases in A2 and A4 tendon and pulley thickness over the last 10 years ($p < 0.001$), while PIP and DIP palmar plate thickness remained unchanged ($p > 0.05$). At the 10-years follow-up, all soft tissue thickness parameters (incl. the palmar plates) were significantly larger in climbers than in age-matched, non-climbing controls ($p < 0.05$). The descriptive and inferential statistics of digit- and side dependent flexor tendon pulley thickness, flexor tendon thickness, palmar plates thickness between the groups of climbers at baseline, climbers at 10 years follow-up and age-matched controls are shown in Figs. 2–4.

3.3. Relationship between soft tissue thickness, age, anthropometrics, years of climbing, age at career start and maximally reached climbing level

At the 10 years follow-up, climbers weighed 72.8 ± 7.2 kg, had 31.6 years of climbing experience and achieved a maximum average redpoint climbing level of 13.7 ± 2.3 (8b). The results of the multiple regression models that examined the association of the current tendon, pulley and palmar plate thickness with the climbers' body weight, years of climbing, and maximally climbing level achieved are presented in Table 1. At $p < 0.05$, there were only significant associations found for average PIP/DIP palmar plate thickness of all digits and hands with body weight and the highest level in sport climbing (redpoint).

4. Discussion

The main findings of this study were: (1) in climbers, a significant increase in A2 and A4 pulley and flexor tendon thickness over the last 10 years was observed, while PIP and DIP palmar plate thickness remained unchanged; (2) at the 10-years follow-up, all soft tissue thickness parameters (incl. the palmar plates) were still significantly larger in climbers than in age-matched, non-climbing controls; (3) a significant association of the current thickness of climber's soft tissues could only be found between palmar plate thickness and reached climbing level, as well as climber's body weight.

4.1. Mechano-adaptation of A2/A4 pulleys, flexor tendons and palmar plates

In the baseline investigation 10 years earlier, our study group reported thicker A2/A4 pulleys, flexor tendons and palmar plates in fingers of elite sport climbers compared to age matched non-

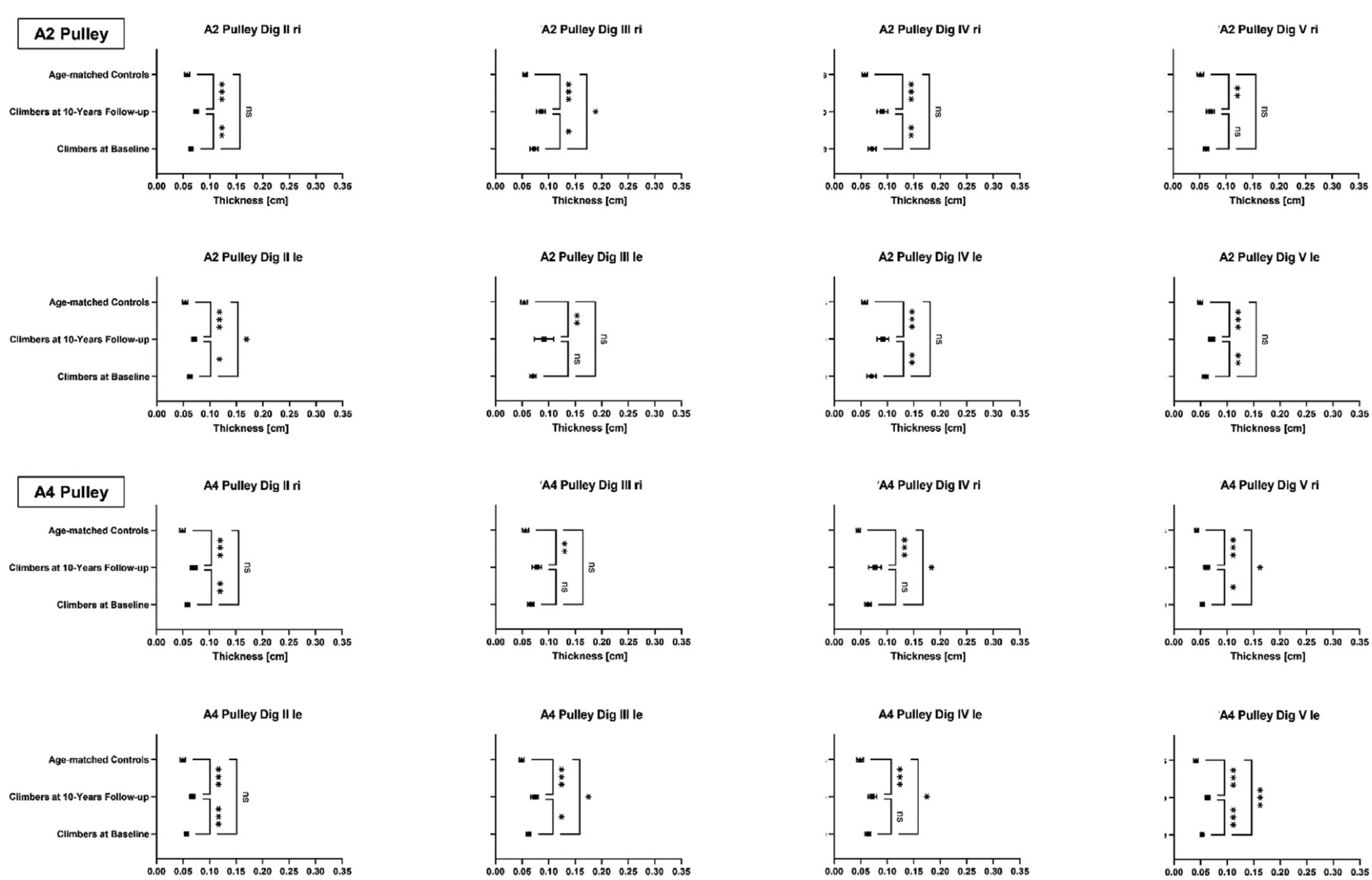

Fig. 3. Descriptive and inferential statistics digit- and side dependent A2 and A4 pulley thickness between the groups of climbers at baseline, climbers at 10 years follow-up and age-matched controls.
Level of significance based on unpaired sample t-tests: ns, not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. PIP: proximal interphalangeal joint; DIP: distal interphalangeal joint; Dig: digitorum; le:left; ri: right.

climbing controls (Schreiber et al., 2015). This was still the case 10 years later, and is entirely in line with earlier studies demonstrating thicker growth plates, palmar plates and flexor tendons in right middle fingers of 20 adolescent rock climbers participating in a competitive local rock-climbing team (Garcia et al., 2018). In addition, Heuck et al. demonstrated thicker capsules, collateral ligaments and up to 50% thicker flexor tendons in 20 sport climbers compared to an age-matched control group (Heuck et al., 1992). Moreover, Klauser et al. demonstrated thicker pulleys compared to a non-climbing control group (Klauser et al., 2000).

As shown in the current study, there has even been a further significant increase in the thickness of A2/A4 pulleys and flexor tendons over the last 10 years. Besides mechano-adaptation of the soft tissues, several studies demonstrated adaptations in other structures of the fingers in sport climbers. Hahn et al. described cortical hypertrophy with smaller medullary canals in elite sport climbers (Hahn et al., 2012). Similar results were published by Schoffl et al. and Bollen et al. who described cortical reactions to mechanical stress in fingers of elite sport climbers (Bollen & Wright, 1994; Schoffl et al., 2007). Finally, our study group demonstrated a remarkable high occurrence of osteophytes and thicker cartilage in PIP and DIP joints of elite sport climbers compared to age-matched controls (Pastor et al., 2020).

Last but not least, it is worth mentioning that the climbers assessed in the current study represent the study sample with the longest climbing history (25–41 years) at elite level reported in the literature to date. As such, our data suggest a career-long buildup of A2/A4 pulley and flexor tendon thickness.

4.2. Correlation between soft tissue mechano-adaptation and climber's anthropometrics

Although there are many studies describing mechano-adaptations in fingers of sport climbers (Allenspach et al., 2011; Bollen & Wright, 1994; Hahn et al., 2012; Morrison & Schoffl, 2007; Pastor et al., 2020; Schoffl et al., 2004, 2007, 2010, 2015, 2018b; Schreiber et al., 2015), evidence on correlations of soft tissue adaptions with anthropometry, performance level and climbing experience of climbers is scarce in the literature. To the best of our knowledge, the current study represents the first attempt to investigate interactions between these parameters. However, contrary to our hypotheses, significant correlations could only be found for palmar plate thickness with climbers' weight and maximum reached red point climbing level. On the one hand, these findings are plausible, as heavier climbers have higher forces acting on their fingers, and higher training and climbing times are necessary to reach higher redpoint levels. On the other hand, there is no reasonable interpretation as to why our data show no correlations between the other soft tissue parameters and the anthropometry, level or experience of the climbers. These partial findings make it, however, difficult to draw a general conclusion concerning correlations between climbers' soft tissue responses (tendons and

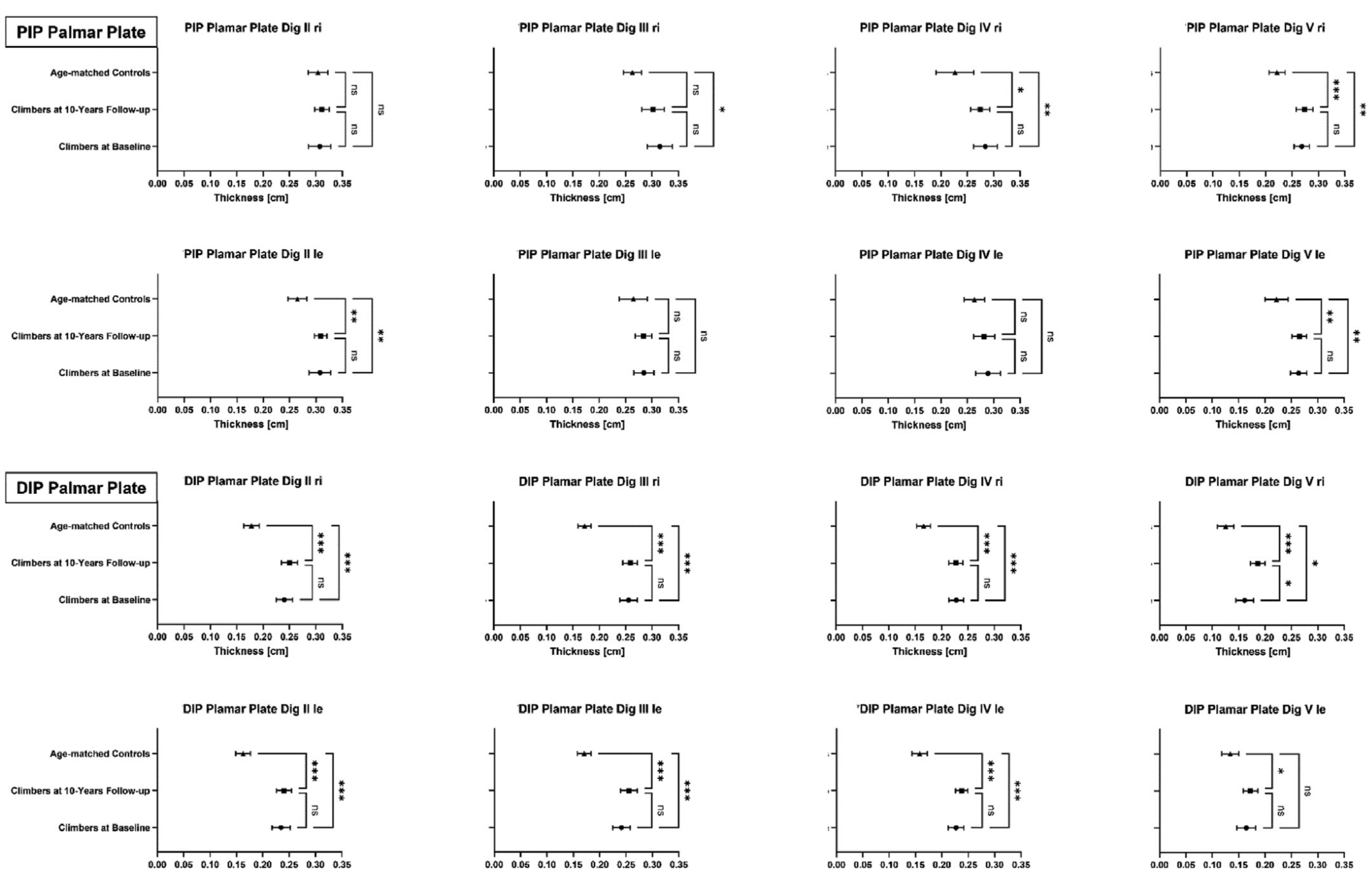

Fig. 4. Descriptive and inferential statistics digit- and side dependent PIP and DIP palmar plate thickness between the groups of climbers at baseline, climbers at 10 years follow-up and age-matched controls.
Level of significance based on unpaired sample t-tests backed up by bias-corrected accelerated (BCa) bootstrapping with 10′000 samples: ns, not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. PIP: proximal interphalangeal joint; DIP: distal interphalangeal joint; Dig: digitorum; le:left; ri: right.

Table 1
Multiple regression analyses evaluating the association of the climbers' current tendon, pulley and palmar plate thickness with age, anthropometrics, years of climbing, age at career start and maximally reached climbing level in elite sports climbers at 10 years follow-up.

Model Parameter	Dependent Variable	Predictor	B	SE_B	β Weight	p-value [b]
Model 1 (tendon) *F = 1.922, p = 0.150, Adjusted R^2 = 0.084, Cohen f (Bollen & Wright, 1994) = 0.092, n = 31*	Average A2/A4 tendon thickness [cm][a]	Body weight [kg]	0.001	0.000	0.252	0.190
		Years of climbing [y]	0.000	0.001	0.004	0.985
		Highest level in sport climbing (redpoint) [–]	0.002	0.001	0.320	0.083
Model 2 (pulley) *F = 0.511, p = 0.678, Adjusted R^2 = -0.051, Cohen f (Bollen & Wright, 1994) = 0.054, n = 31*	Average A2/A4 pulley thickness [cm][a]	Body weight [kg]	0.000	0.000	0.095	0.641
		Years of climbing [y]	0.001	0.001	0.180	0.382
		Highest level in sport climbing (redpoint) [–]	−0.000	0.001	−0.008	0.969
Model 3 (palmar plate) *F = 5.542, p = 0.004, Adjusted R^2 = 0.312, Cohen f (Bollen & Wright, 1994) = 0.453, n = 31*	Average PIP/DIP palmar plate thickness [cm][a]	Body weight [kg]	0.002	0.001	0.507	0.004
		Years of climbing [y]	−0.001	0.001	−0.138	**
		Highest level in sport climbing (redpoint) [–]	0.004	0.002	0.347	0.409 0.032 *

[a] Data represents the averaged thickness of all measured locations, digits and both sides.
[b] Level of significance backed-up by bias-corrected accelerated (BCa) bootstrapping with 10′000 samples:*p < 0.05; **p < 0.01.

pulleys) and their anthropometry, performance levels and lifetime climbing volumes. Larger study populations may fill this knowledge gap in future studies.

5. Methodological considerations

Although we have achieved a follow-up rate of 100% over 10 years, some possible limitations should be considered when interpreting the study results. First, ultrasonography was performed by two different examiners 10 years ago and now. Even all examinations were highly standardized and conducted by very experienced examiners under the direct supervision of author 2 (A.S.) who was involved in both studies, inter-observer bias still may have been possible. However, one big advantage is the fact that all examinations were performed by the same study group using the same technical devices and protocols to minimize discrepancies. Technically and organizational, it was not possible to carry out this study otherwise. With respect to validity of the ultrasound methodology used, a previous study reported the mean absolute error between clinical high-frequency ultrasound and digital caliper measurements on cadavers (ground truth) to be 0.10 mm (Yang et al., 2016), while the group differences in tendon and pulley thickness in our study typically ranged from 0.10 mm to 0.71 mm. Second, due to a relatively small sample size of 31 elite male climbers the generalizability of the current findings for other cohorts (e.g. female elite climbers) may be limited. Third, our control group from 10 years earlier could not be recruited again for another evaluation. To compensate for this, we recruited a new age-matched control group of 15 non-climbers. Fourth, because hands of elite climbers are immediately recognizable, it was not possible to blind the examiners, leaving a potential bias due to a lack with respect to blinding during ultrasound examination.

6. Conclusion

An accumulation of repetitive climbing-related stress to the fingers of elite sport climbers over the career may induce mechano-adaptation of the A2/A4 pulleys, flexor tendons and palmar plates. At later stages of the career, further significant increase of flexor tendon and pulley thickness but not for palmar plate thickness were observed. However, a correlation between this mechano-adaptation and the anthropometry, level and experience could only be found for palmar plate thickness with body weight as well as with highest redpoint level reached.

Ethics approval

This study was approved by the local ethics committee (KEK Zürich, Switzerland, BASEC-Nr. 2019-00677) and was carried out in accordance with the Declaration of Helsinki. All participants provided their written informed consent.

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Data availability statement

All data relevant to the study are included in the article or uploaded as supplementary information.

Declaration of competing interest

None.

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