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Biomechanical properties of the crimp grip position in rock climbers

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Abstract

Rock climbers are often using the unique crimp grip position to hold small ledges. Thereby the proximal interphalangeal (PIP) joints are flexed about 90° and the distal interphalangeal joints are hyperextended maximally. During this position of the finger joints bowstringing of the flexor tendon is applying very high load to the flexor tendon pulleys and can cause injuries and overuse syndromes. The objective of this study was to investigate bowstringing and forces during crimp grip position. Two devices were built to measure the force and the distance of bowstringing and one device to measure forces at the fingertip. All measurements of 16 fingers of four subjects were made in vivo. The largest amount of bowstringing was caused by the flexor digitorum profundus tendon in the crimp grip position being less using slope grip position (PIP joint extended). During a warm-up, the distance of bowstringing over the distal edge of the A2 pulley increased by 0.6 mm (30%) and was loaded about 3 times the force applied at the fingertip during crimp grip position. Load up to 116 N was measured over the A2 pulley. Increase of force in one finger holds by the quadriga effect was shown using crimp and slope grip position.

Keywords: Rock climbing; A2 pulley; Bowstringing; Flexor tendon sheath

1. Introduction

Rock climbing and indoor climbing became very popular in the past years. The difficulties of the routes increased to an extent that almost only professionals are able to succeed. According to this the demand on the bones, joints and soft tissue of the fingers increased significantly (Bollen, 1990). The main part of the body weight has to be held sometimes only with the distal phalanx at small ledges or pockets of the depth of only a few millimetre. Up to 90% of rock climbers are using the crimp grip (Fig. 1) position where the proximal interphalangeal (PIP) joints are flexed from 90° to 100° and the distal interphalangeal (DIP) joints are hyperextended to hold such small grips (Bollen, 1988; Marco et al., 1998). The second most often used grip form is the slope grip (Fig. 2) where the DIP joints are flexed form 50° to 70° and where the PIP joints are extended or flexed just slightly. There are also other possibilities to hold a grip but the biomechanical properties and injury pattern of the crimp grip position is unique.

Several different reasons favour the crimp grip in comparison with the slope grip position. A small ledge with a sharp edge and a rather concave shape in the longitudinal axis of the distal phalanx is hold in this manner because it prevents the edge to cut in the skin which would be very painful. The use of the thumb as an additional holding force is possible only while the long fingers are in the crimp grip position. In order to gain the highest contact area and the best friction between the pulp of the finger on the rock and to compensate the different length of the long fingers, it is necessary to crimp one or more fingers to a different extent. Flexion of the PIP joint increases the moment arm of the flexor tendons in this joint (An et al., 1983; Mester et al., 1995) and increases the holding force. The most effective and powerful angle at which the PIP joint is between 90° and 110° as occurring in crimp grip. The slope grip, in comparison, is used effectively to hold round and anatomically shaped grips as well as finger pockets without sharp edges. The force required of the flexor digitorum profundus (FDP) tendon across the DIP joint against an external force at the fingertip is much lower theoretically as the force across the PIP joint (Fig. 3) to reach equilibrium. The grip form which is similar to the slope grip seems to be more physiological and probably does not have the same risk of injury of the flexor tendon sheath and pulleys.

The high amount of load on the fingers while using the crimp grip is unique in rock climbers and does not occur

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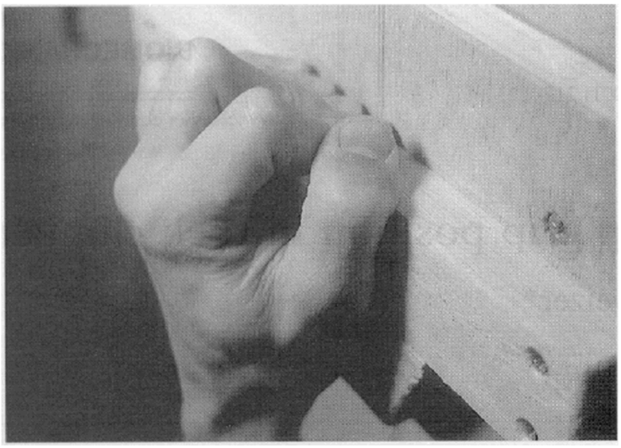

Fig. 1. The crimp grip position, performed on a small ledge of depth of 2 cm. The typically flexed PIP and hyperextended DIP joint is visible. The thumb is acting as an additional holding force.

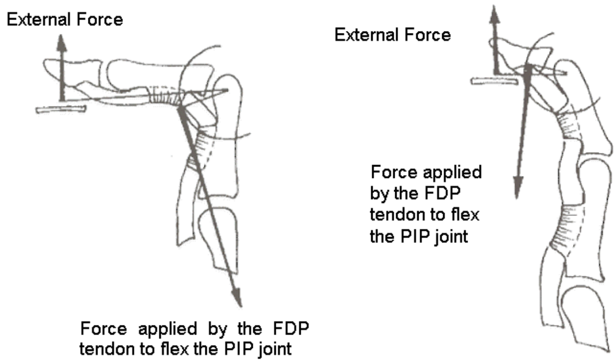

Fig. 3. Moment arms of the FDP tendon across the PIP and the DIP joint in relation to moment arms of external force at across the PIP and DIP joint, crimp grip position on the left, slope grip on the right. While using the slope grip position less force of the of the FDP tendon is required to reach equilibrium.

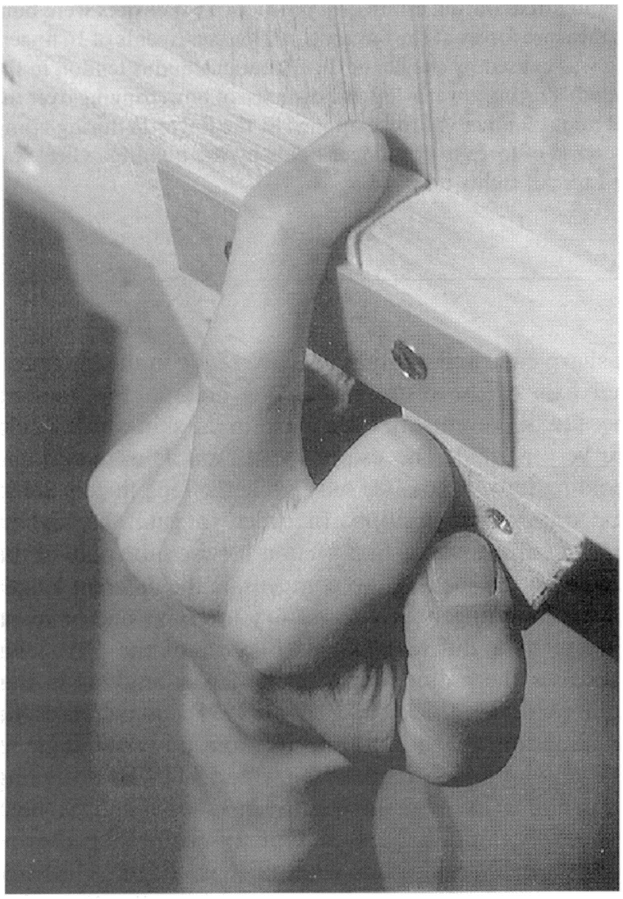

Fig. 2. Slope grip position, one finger isolated pulling on a ledge where a piezoelectric sensor can measure the force acting at the tip of just one finger. The typically extended PIP and flexed DIP joint is visible.

in any other sport or profession. It has not been investigated intensively in vivo. The distance and force of physiological bowstringing in vivo as well as the forces at the fingertip using different grip modalities was investi- gated in this study.

2. Materials and methods

The physiologically occurring bow stringing is well palpated over the course of the flexor tendon sheath as the finger is flexed. It can be determined by the distance from the bone to the flexor tendons and by the force which acts perpendicular to the flexor tendons and causes bowstringing. These parameters were measured by two custom made devices in vivo. The distance of bowstringing along the flexor tendon sheath in the crimp grip and slope grip position as well as the force of bowstringing over the distal edge of the A2 pulley was measured. The A2 pulley is the main annular ligament over the proximal phalanx and is together with the A4 pulley (middle phalanx) the most important restraint of bowstringing of the flexor tendons (Fig. 9). A further device was built to measure the force acting between the grip and the tip of the finger. Different types of grips were investigated. Changes of the distance of bowstringing during a warm up was investigated finally.

2.1. Distance measuring device for bowstringing

This custom made device was composed of two parts, which moved against one another around a central axle in a scissors-like fashion. The finger was clamped by two measuring arms in an anterior-to-posterior direction was compressed constantly by a spring. The force applied by the spring did not increase compression by more than 0.1 mm and did not disturb physiological bowstringing during measurement. As bowstringing occurred, the two arms were pushed apart and the distance was measured by a nonius scale. The accuracy of the device was

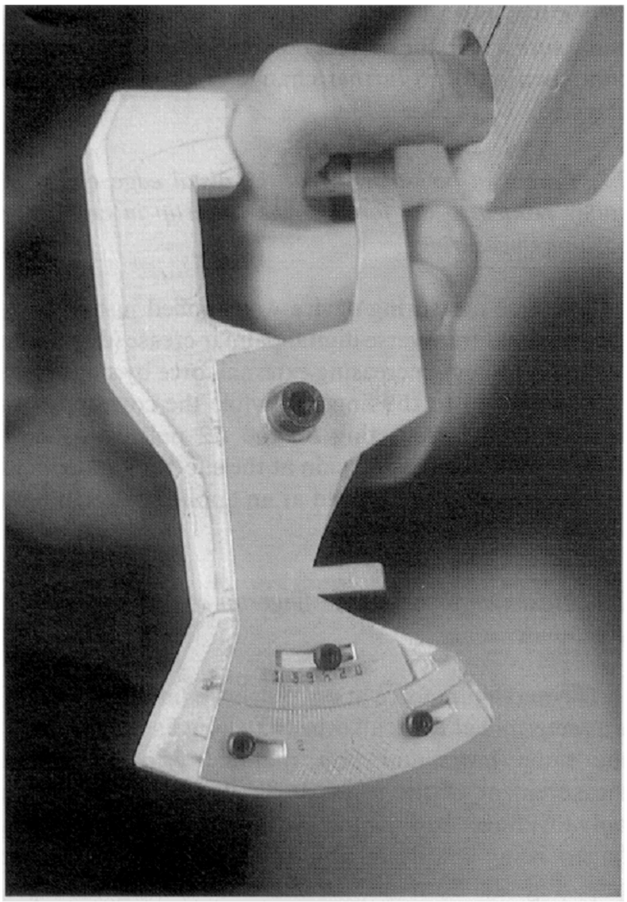

Fig. 4. Distance measuring device applied for measurement in crimp grip position. The contact area with the skin at the flexor surface is 5 mm in the axial direction and is concave in the transverse plane; the edges are rounded off.

0.05 mm. The external force at the fingertip was increased to an extent that no further bow stringing could be detected (about 30 N). In order to prevent displacement of the device, the angels of flexion of the finger joints must not be changed after application of the device (see Fig. 4).

2.2. Force measuring device for bowstringing

This custom-made device was composed of two main parts, which moved against one another around an axle in a clamp-like fashion. The finger was compressed by the two arms in an anterior-to-posterior direction with 10 N of force provided by a spring. This was necessary for the force on the flexor tendons to be measured by the device. After the application of the device, the two arms were locked against one to another by a fixation screw. One of the two arms consisted of a steel plate provided with a strain gauge transducer. As bowstringing occurred, the steel plate was minimally deformed and this was detected by the strain gauge transducer. The signal was amplified and the force could be calculated. The range of

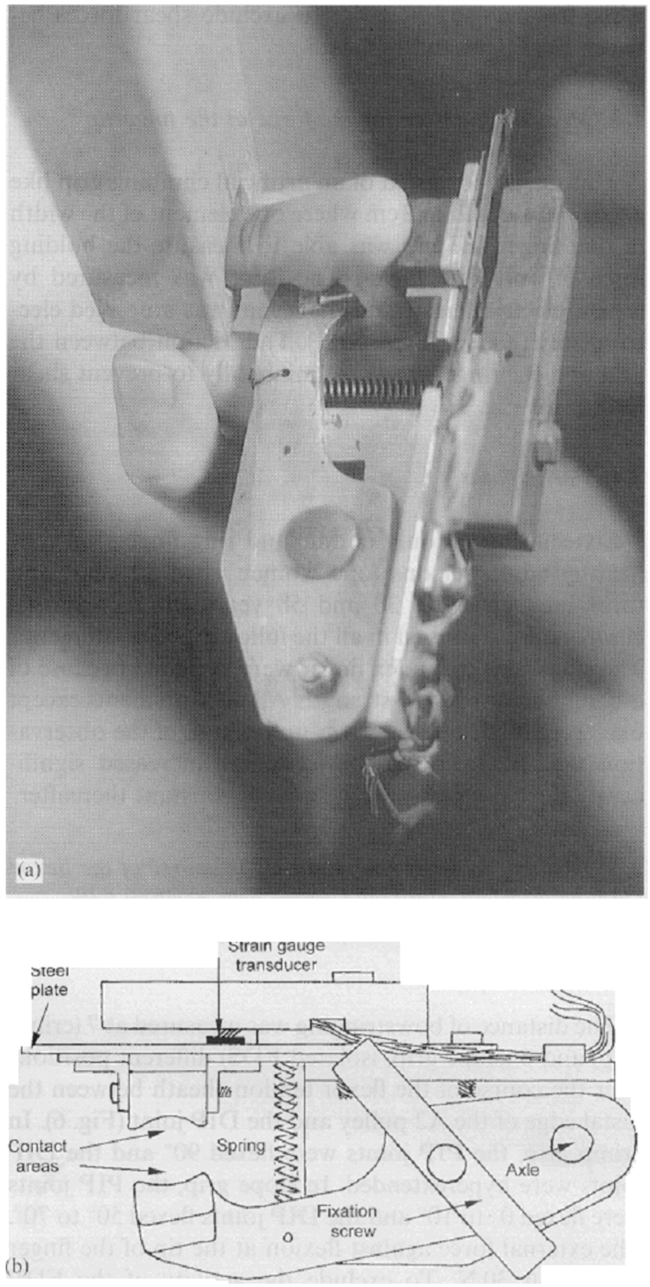

Fig. 5. a,b Force measuring device applied for measurement in crimp grip position. The contact area with the skin at the flexor surface is 9 mm. It is slightly convex in the axial direction and concave in the transversal plane; the edges are rounded off. After the device has been placed, the two arms are fixed to one another by a screw. The tip of the finger is placed in the hole of a wooden slat with a spring scale which measures the applied external force.

linear measurement was 0-400 N, the accuracy was 0.3 N (see Fig. 5a and b).

To apply a controlled external force against flexion to the tip of the finger, a hole of 22 mm depth and diameter was made in a wooden slat. The slat was fixed to a commercial spring scale of a range of measurement of 0-200 N and an accuracy of 1 N. The slat was movable while free hanging in order to exclude shear forces between the finger and the slat.

2.3. Measuring device for the force at the fingertip

This device consisted of an artificial climbing grip like a ledge of a depth of 2cm where one element of the width of one finger (2.3 cm) was able to measure the holding force of only one finger. The force was measured by a piezoelectric sensor and the signal was amplified electronically (Kistler Type 5011). The friction between the grip and the finger was kept minimally to prevent shear forces (see Fig. 1).

2.4. Participants

Sixteen fingers (only middle and ring fingers) in four healthy adult persons (one women aged 30 year, and three men aged 30, 30 and 58 years, all recreational climbers) were studied in all the following measurements. The small and the index finger were excluded because of different anatomy and strength. All measurements except one, were made after a warm-up because of the observation that physiological bowstringing increased significantly during warm-up but became constant thereafter.

2.5. Distance of bow stringing over the course of the flexor tendons in crimp, slope and crimp grip position with isolated flexor digitorum superficialis (FDS) activity (measuring)

The distance of bow stringing was measured at 7 (crimp grip) and 6 (slope grip, isolated FDS) different positions over the course of the flexor tendon sheath between the distal edge of the A2 pulley and the DIP joint (Fig. 6). In crimp grip, the PIP joints were flexed 90° and the DIP joints were hyperextended. In slope grip, the PIP joints were flexed 0° to 10° and the DIP joints flexed 50° to 70°. The external force against flexion at the tip of the finger was about 30 N. To exclude the activity of the FDP tendon in the isolated FDS crimp grip position the external force was applied directly under the DIP joint while the other four long fingers were maximally extended as in the quadriga manoeuvre.

2.6. Distance of bow stringing over the distal edge of the A2 pulley during a warm up (measuring)

Bowstringing just distal to the proxImal transverse digital palmar crease (distal edge of the A2 pulley) was measured during a warm up in crimp grip position (PIP joint 90° flexed, DIP joint hyperextended). The warm-up was performed at a 20° overhanging artificial climbing wall. The measurements were done in the crimp grip position each time after 20 climbing moves, while the device was placed newly before every measurement to make sure it is in the correct position. The procedure was continued until no further change of bowstringing was detected.

2.7. Forces of bowstringing at the distal edge of the A2 pulley related to the force at the fingertip in crimp grip position (measuring)

The force measuring device was applied just distal to the proximal transverse digital palmar crease (distal edge of the A2 pulley). Increasing external force by steps of 4.9 N was applied to the fingertip while the corresponding bowstringing force acting on the A2 pulley was measured. Due to increasing pain at the site of measurement, the study had to be stopped at an applied external force above 29.4 N.

2.8. Maximum forces at the fingertip of dzfferent types of grips (measuring)

The maximum force at one fingertip (middle and ring) was determined while all other long fingers were acting at the same horizontal grip (parallel grip). A second measurement of the same finger was performed while only this finger had contact with the grip, the other long fingers being in a flexed and unloaded position (isolated grip, Fig. 2). Both measurement modalities were performed in crimp and slope grip positions.

3. Results

All results in millimetre (mm) and Newton (N) are written as mean an standard deviation in parenthesis.

3.1. Distance of bowstringing over the course of the flexor tendons in crimp, slope and crimp grip position with isolated FDS activity

The distance of bow stringing was most apparent in the crimp grip position where it reached 4.3 (0.7) mm over the PIP joint. It was almost absent 0.2 (0.15) mm at the same measuring site in the slope grip position. Bowstringing over the PIP joint was considerably less distinct in isolated FDS activity during crimp grip 1.75 (0.75) mm over the PIP joint (see Fig. 6, Table 1).

3.2. Distance of bow stringing over the distal edge of the A2 pulley during a warm up

Bowstringing increased from 1.15 (0.15) to 1.75 (0.15) mm (30%) after 100 climbing moves (50 cyclic loads for each hand) and did not increase significantly thereafter (see Fig. 7).

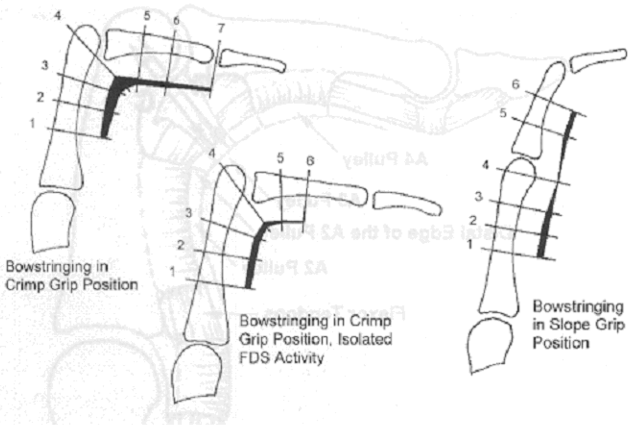

Fig. 6. Distances of bowstringing of different grip positions along the flexor tendon sheath. The black coloured area indicates the distance of bowstringing. Sites of measurement: (1) over the proximal digital palmar crease, at the distal edge of the A2 pulley; (2) in the middle between 1 and 3; (3) proximal adjacent to the trochlea of the proximal phalanx which is palpated at the volar side; (4) over the PIP joint on the dorsal side directly over the knuckle, on the volar side over the middle digital palmar crease; (5) distal to the base of the middle phalanx which is palpated on the volar side; (6) in the middle between 5 and 7; and (7) directly over the DIP joint over the distal digital palmar crease.

Table 1
Distances of bowstringing of 16 middle and ring fingers in crimp grip position, slope grip position and crimp grip position with isolated FDS activity. Positions of measurements 1-7 according to Fig. 6. Results mean (S.D.) in mm

Position	Crimp grip	Slope grip	Crimp grip, isolated FDS
1	1.65 (0.35)	1.65 (0.3)	1.25 (0.45)
2	2.2 (0.45)	1.6 (0.3)	1.5 (0.4)
3	3.35 (0.7)	1.65 (0.45)	1.85 (0.4)
4	4.3 (0.7)	0.2 (0.15)	1.75 (0.75)
5	1.35 (0.35)	1.05 (0.4)	0.25 (0.15)
6	1.05 (0.5)	0.9 (0.3)	0.2 (0.15)
7	0.85 (0.45)		

3.3. Forces of bowstringing at the distal edge of the A2 pulley related to the force at the fingertip in crimp grip position

The force of physiological bowstringing in relation to external applied force to the tip of the finger was 116 (11) N at an external force of 30 N and showed a constant linear gradient. Further increase of external force was not possible due to the pain caused by the compression of the measuring device (see Fig. 8).

3.4. Maximum forces at the fingertip of different types of grips

The maximum forces at one fingertip for isolated crimp grip was 96 (21) N and for isolated slope grip 116

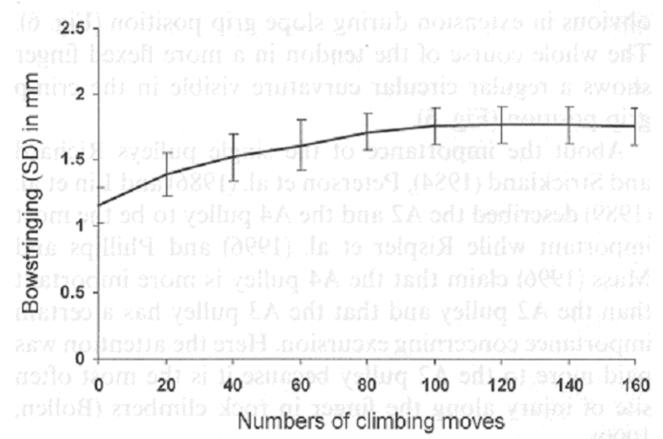

Fig. 7. Distance of bowstringing over the distal edge of the A2 pulley during a warm-up. Climbing moves were done alternating the left and the right hand, each grip was held for l-2 s.

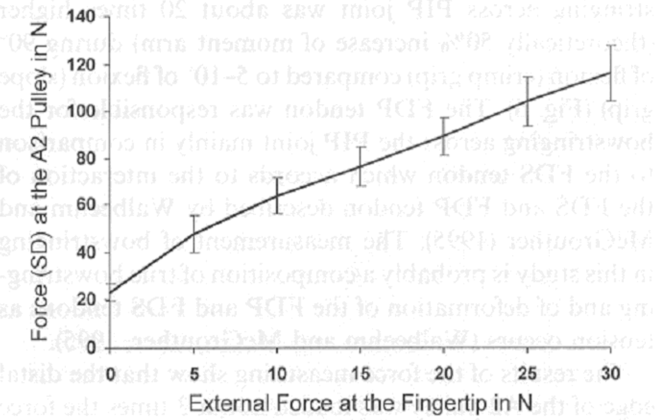

Fig. 8. Force of physiological bowstringing acting on the distal edge of the A2 pulley; External force in N against flexion applied at the pulp of the distal phalanx horizontally; Force component of flexor tendons in N, which causes bowstringing vertically.

(30) N. The maximum forces at one fingertip for parallel crimp grip was 82 (19) N and for parallel slope grip was 78 (22) N. The force of the isolated crimp grip was 17% higher in comparison with the parallel crimp grip and the force of the isolated slope grip was 48% higher in com- parison with the parallel slope grip.

4. Discussion

Several studies on the anatomy and biomechanics of the flexor tendon sheath have been carried out. After Doyle and Blythe (1975) and Strauch and de Moura (1985) described the anatomy of the pulley system, Manske and Lesker (1977) determined it even in more detail. Lin et al. (1989) described a joint and bony-type bowstringing which is not only occurring over a flexed joint but also along the phalanx the tendon being nearest to the bone at the middle of the phalanx in the sagittal plane. In this study, a bony-type of bow stringing was obvious in extension during slope grip position (Fig. 6). The whole course of the tendon in a more flexed finger shows a regular circular curvature visible in the crimp grip position (Fig. 6).

About the importance of the single pulleys Richard and Strickland (1984), Peterson et al. (1986) and Lin et al. (1989) described the A2 and the A4 pulley to be the most important while Rispler et al. (1996) and Phillips and Mass (1996) claim that the A4 pulley is more important than the A2 pulley and that the A3 pulley has a certain importance concerning excursion. Here the attention was paid more to the A2 pulley because it is the most often site of injury along the finger in rock climbers (Bollen, 1990).

The results of this study do support the statement of An et al. (1983) and Mester et al. (1995), who showed that the moment arm of the flexor tendons over the PIP joint increased during flexion because the distance of bowstringing across PIP joint was about 20 times higher (theoretically 50% increase of moment arm) during 90° of flexion (crimp grip) compared to 5-10° of flexion (slope grip) (Fig. 6). The FDP tendon was responsible for the bowstringing across the PIP joint mainly in comparison to the FDS tendon which accords to the interaction of the FDS and FDP tendon described by Walbeehm and McGrouther (1995). The measurement of bowstringing in this study is probably a composition of true bowstringing and of deformation of the FDP and FDS tendons as tension occurs (Walbeehm and McGrouther, 1995).

The results of the force measuring show that the distal edge of the A2 pulley was loaded about 3 times the force applied at the fingertip during crimp grip position which corresponds to the results of Hume et al. (1991). At 25% of maximum strength of flexion in crimp grip position the load to the distal edge of the A2 pulley was about 120 N. The graph showed a linear increase. It was assumed that further increase of external force to the tip of the finger (which was not possible due to increasing pain) would not change the direction of the graph. On this assump- tion, the force of bow stringing was calculated to be 373 N for an external resistance of 118 N at the fingertip which is in the range of the maximum force of the finger flexors of a recreational climber. This would imply a maximum load to the A2 pulley of almost 400 N theoretically. This corresponds almost to the calculated force of 450 N (Bollen, 1990) and is near to the maximum strength of the A2 pulley of 407 N (Lin et al., 1990) or 375 N (Tang, 1995). The high loads to the pulleys near maximum strength using the crimp grip means that pulleys in vivo may probably be much stronger than the pulleys of aged and cadaver fingers used in the above-named other studies. The pulleys of professional rock climbers may be even much stronger because the loads to their fingers being far beyond the maximum strength named above.

Bollen (1990) reported about rock climbers with increased bowstringing due to assumed rupture of the A2 pulley. Nevertheless, they had no functional deficit. Increase of bowstringing, however, may lead to the loss of range of motion and may be a indication for reconstruction. Marco et al. (1998) reported that an isolated rupture of a pulley is unlikely to happen and that an obvious bowstringing is possible only after the rupture of the A2, A3 and A4 pulleys. The distance measuring device used in this study may be helpful to detect changes of bowstringing in order to localise and diagnose ruptures of pulleys.

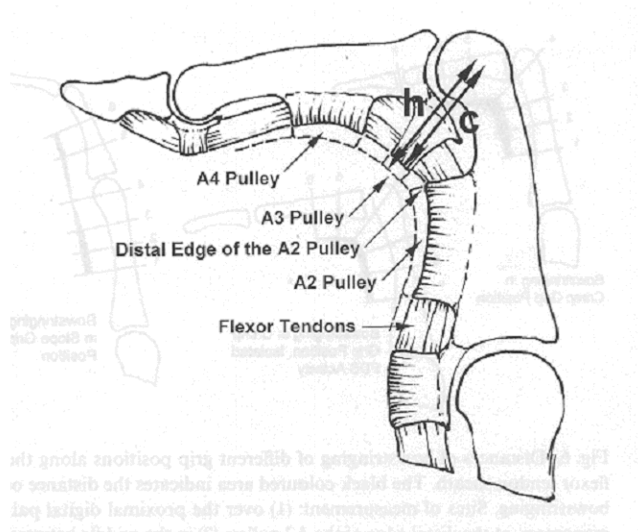

Fig. 9. Arrangement of A2, A3 and A4 pulleys along the flexor tendon sheath, Bowstringing of the flexor tendons before (c) and after a warming up (h, + 0.6 mm, dashed line) which led to an increase of the moment arm of the FDP tendon across the PIP joint of 3%.

After a warming-up, the course of the tendon could become more even and regular preventing peak forces at distinct points of the flexor tendon sheath. In addition to this, the following important fact was found in this study. During a warm-up, the distance of bowstringing over the distal edge of the A2 pulley in the crimp grip position increased by 0.6 mm (30%, from 1.15 to 1.75 mm) after about 100 climbing moves which accords to 50 cyclic loads in crimp grip for each hand. This was not accomp- lished by any other warming-up technique. At least three middle to long routes have to be climbed to achieve 100 moves, to get warmed-up and to be ready for maximum loads in the area of the flexor tendon sheath. Concerning the moment arm of the FDP at the PIP joint it implies a small but theoretically increase of 3 % (Fig. 9).

Increase of force and load up to 48% in one finger holds compared to all finger holds was detected during crimp grip as well as slope grip position. This supports the theory of the quadriga effect described by Verdan (1960). The muscles and tendons of the FDP which are connected one to another (Brand and Hollister, 1993) increase the actual force of the muscle of one tendon significantly. Maximum force of isolated slope grip was about 20% higher than in isolated crimp grip position which supports the theory that the muscle force of the FDP tendon is more effective using the slope grip than the crimp grip position (Fig. 3).

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