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Friction between human finger flexor tendons and pulleys at high loads

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Abstract

A method was developed to indirectly measure friction between the flexor tendons and pulleys of the middle and ring finger in vivo. An isokinetic movement device to determine maximum force of wrist flexion, interphalangeal joint flexion (rolling in and out) and isolated proximal interphalangeal (PIP) joint flexion was built. Eccentric and concentric maximum force of these three different movements where gliding of the flexor tendon sheath was involved differently (least in wrist flexion) was measured and compared. Fifty-one hands in 26 male subjects were evaluated. The greatest difference between eccentric and concentric maximum force (29.9%) was found in flexion of the PIP joint. Differences in the rolling in and out movement (26.8%) and in wrist flexion (14.5%) were significantly smaller. The force of friction between flexor tendons and pulleys can be determined by the greater difference between eccentric and concentric maximum force provided by the same muscles in overcoming an external force during flexion of the interphalangeal joints and suggests the presence of a non-muscular force, such as friction. It constitutes of 9% of the eccentric flexion force in the PIP joint and therefore questions the low friction hypothesis at high loads.

1. Introduction

The aim of the specialisation of the human finger flexor tendon and its sheath is assumed to keep friction to a minimum for optimal functionality. However there are some hints indicating that the presence of friction may be also of functional value. For instance the interaction of the flexor tendons and flexor tendon sheath in chiropterans (bats) represent a specialisation where friction allows those animals to dangle on their fingers without muscular activity by a so-called tendon locking mechanism (TLM) (Quinn and Baumel, 1990, 1993). The presence of friction would explain also why rock climbers can resist immense forces by the finger flexors during the grip of very small holds although they do not show proportionally greater concentric muscular force compared to non-climbing subjects (Watts et al., 1996). Furthermore, friction would explain the mechanism of injury to the A2 pulleys in rock climbers more exactly (Bollen, 1990; Gabl et al., 1998), (A2 pulley: annular like ligament, part of the flexor tendon sheath, at the volar side of the proximal phalanx, prevents flexor tendons from bowstringing). Until now there is only evidence that friction between flexor tendons and pulleys may be apparent in a few in vitro measurements (Uchiyama et al., 1995, 1997).

The purpose of this study was to develop a method to determine the effect of friction between human finger flexor tendons and pulleys of the middle and ring finger in vivo and during high load. The estimation of friction in this study is based on the following concept of a quasi-static situation. During eccentric flexion movement, the flexor tendon tends to glide distally resulting in a friction force (between A2 pulley and flexor tendon) directing proximally, in the same direction as the muscular force. The external resistance therefore measures the sum of these two forces. However, during concentric flexion movement, the flexor tendon tends to glide proximally resulting in a friction force directed distally. The external resistance is therefore the difference between frictional force and muscular force. The difference between eccentric and concentric maximum force generated is therefore composed mainly on physiological muscular properties, state of individual muscular condition or training, joint friction, and

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friction between movable soft tissue parts like the flexor tendon sheath of the finger. Three different exercises in which the flexor tendon sheath is involved differently while using the same muscles were investigated (although in wrist flexion additional muscles come into play: musculi flexor carpi ulnaris, flexor carpi radialis and flexor palmaris longus). The strain difference of the flexor tendons through the carpal tunnel in a neutral position of the wrist (where also the peak forces and moments during these measurements occur) is known to be minimal (0.25% during in vitro measurements, according to Goldstein et al. (1987)).

The hypothesis is that differences between eccentric to concentric forces and moments would be greater in a movement where gliding of the flexor tendon sheath is involved than in one where this is not so. Frictional force originating from the flexor tendon sheath could be the possible cause of that difference. Quantification of that force could be estimated in relation to the maximum muscle force measured. Such in vivo measurements would exclude a preconditioning effect and an alteration of in vitro measurements (Black, 1976). To our knowledge no work has been done on in vivo friction measurements between flexor tendons and pulleys at high loads.

2. Materials and methods

2.1. Quantification of frictional force and coefficient of friction

For the present purpose both flexor muscles, the deep and the superficial, will be considered acting together, this total force being F_M. Also, it is assumed that the moment arm length of each of the muscles, as well as that of the frictional force (F_R) are the same (r_2). Assuming that friction is the same for eccentric and concentric movement, the frictional moment (r_2F_R) in concentric finger flexion for the PIP joint (Fig. 1) results from the difference of flexor muscle moment (r_2F_M) and the external resistance moment (r_1F_E), the moment of friction being in an opposite direction to the gliding direction of the tendon (r_1 = distance from PIP center of rotation to tip of the finger, $r_1 = 45$ mm; r_2 = perpendicular component from PIP center of rotation to distal edge of A2 pulley, $r_2 = 10$ mm). Friction in the PIP joint, skin and ligaments is assumed to be minimal and is neglected. Following equation can be composed:

$$r_1 F_{\mathrm{E\ con}} = r_2 F_{\mathrm{M\ con}} - r_2 F_R. \tag{1}$$

For eccentric finger flexion in PIP joint

$$r_1 F_{\mathrm{E\ ecc}} = r_2 F_{\mathrm{M\ ecc}} - r_2 F_R, \tag{2}$$

$$r_1 F_{\mathrm{E\ ecc}} - r_1 F_{\mathrm{E\ con}} = r_2 D + 2 r_2 F_R. \tag{3}$$

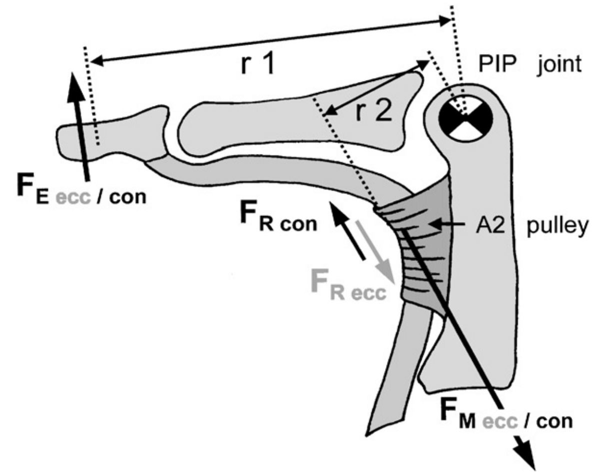

Fig. 1. Moments acting at the PIP joint during resisted eccentric and concentric flexion. During eccentric flexion, friction force $F_{R\,\mathrm{ecc}}$ acted in the same direction as the muscular force $F_{\mathrm{M\ ecc}}$ while during concentric flexion friction force $F_{R\,\mathrm{con}}$ acted in a direction opposite to the muscular force $F_{\mathrm{M\ con}}$.

Estimation of friction between the flexor tendon and pulleys during PIP flexion can therefore theoretically be determined from the difference between eccentric and concentric maximum moments and the external moment applied. A strength deficit (D) is defined as ($F_{\mathrm{M\ ecc}} - F_{\mathrm{M\ con}}$), which could be determined through other means.

The strength deficit (D) can be estimated, for instance by the known strength deficit coefficient (d) during wrist flexion about the neutral position, where friction is known to be minimal (Goldstein et al., 1987) in spite of some other muscles coming into play as well (musculi flexor carpi ulnaris, flexor carpi radialis, flexor palmaris longus).

$$d = \frac{F_{\mathrm{wrist\ flex\ con}}}{F_{\mathrm{wrist\ flex\ ecc}}}. \tag{4}$$

However, it must be stated that the estimation of (d) is the major uncertainty factor in this study. Eccentric muscular force ($F_{\mathrm{M\ ecc}}$) can be obtained by concentric muscular force ($F_{\mathrm{M\ con}}$) and the known strength deficit coefficient (d), from Eq. (4)

$$D = F_{\mathrm{M\ ecc}} - dF_{\mathrm{M\ ecc}} = F_{\mathrm{M\ ecc}}(1 - d). \tag{5}$$

From Eqs. (3) and (5) follows:

$$r_1 F_{\mathrm{E\ ecc}} - r_1 F_{\mathrm{E\ con}} = 2 r_2 F_{\mathrm{R}} + r_2 F_{\mathrm{M\ ecc}}(1 - d). \tag{6}$$

Using Eq. (2), substitution of $r_2 F_{\mathrm{M\ ecc}}$ in Eq. (6) leads to

$$r_1 F_{\mathrm{E\ ecc}} - r_1 F_{\mathrm{E\ con}} = 2 r_2 F_R + (r_1 F_{\mathrm{E\ ecc}} + r_2 F_R)(1 - d). \tag{7}$$

Friction force (F_R) can be obtained

$$F_R = \frac{r_1 (dF_{\mathrm{E\ ecc}} - F_{\mathrm{E\ con}})}{r_2 (1 + d)}. \tag{8}$$

The coefficient of friction (μ) for eccentric flexion can be determined as follows, assuming that the graph is linear (linear increase of gliding resistance between tendon and pulley, Uchiyama et al., 1997) and passes through zero, α represents the arc of contact between the flexor tendon and the pulleys

$$r_1 F_{\mathrm{E\ ecc}} = r_2 F_{\mathrm{M\ ecc}} + r_2 F_R = r_2 F_{\mathrm{M\ ecc}} \mathrm{e}^{\mu\alpha}. \quad (9)$$

Friction coefficient (μ) according to Uchiyama et al. (1995) is therefore

$$\begin{aligned} \mu &= \mathrm{Ln}(r_1 F_{\mathrm{E\ ecc}} / r_2 F_{\mathrm{M\ ecc}})/\alpha \\ &= \mathrm{Ln}(r_1 F_{\mathrm{E\ ecc}} / r_1 F_{\mathrm{E\ ecc}} - r_2 F_R)/\alpha. \end{aligned} \quad (10)$$

2.2. Subjects

Fifty-one hands in 26 male subjects, average age 32.6 years (range 16.9–45.3 yr, SD 7.9 yr), were investigated. Exclusion criteria were acute or chronic injuries in the wrist or fingers. In order to exclude the factor of low motivation during maximum force measurement, all subjects were active rock climbers interested in the investigation. Secondly, the reason for choosing rock climbers as subjects is that they all have well trained finger and wrist flexors which minimise eccentric to concentric strength deficits (Buehrle et al., 1985).

2.3. Isokinetic movement device

The isokinetic movement device consisted of a $70 \times 50 \times 55\,\mathrm{cm}^3$ frame that held the motor/gear box unit and the electronic control system (Fig. 2). Three different frame-like boxes were built which could be coupled to the device unit. Each of the boxes allowed one of the specific movements, wrist flexion (Fig. 3), rolling a bar in and out (Fig. 4), and isolated flexion in the PIP joint (Fig. 5). The movement boxes were connected to the device unit by a cable wire to which a force transducer was attached (Fig. 2). A Zuerrer TFVB9-55/2 three-phase electric cage motor (630 W) coupled to a worm gear (Zuerrer 2/1MH) with an output torque of at least 30 N m maintained constant speed during measurements. The speed of the device unit was controlled by a frequency converter (Hardmeier control VF61M R722). Force transmission from the device unit to the movement device box occurred through a tie-rod providing a sinus-like oscillation. This movement pattern was chosen for safety reasons (no uncontrolled increase of range of motion was possible). Furthermore, a forced sinusoidal movement (desmodrom) is much easier to perform than a truly isokinetic movement where the velocity remains strictly constant making a change of the direction of movement more difficult (Goehner, 1995).

The first movement box (Fig. 3) allowed the measurement of eccentric and concentric flexion moment of the wrist. A comfortable anatomically shaped handle, which could be grasped firmly allowed maximum force transmission from the flexors of the fingers and wrist to the movement device. The handle was in 20° ulnar deviation so that the axle of the device was parallel to the plane of the articular surface of the distal radius. The dorsum of the forearm was placed on a board that acted as a counter-arm against flexion movement. Range of motion was 30° extension and 30° flexion. This movement was designed to keep friction between the flexor tendons and the pulleys of the fingers minimally by not moving the concerning joints and therefore preventing tendon gliding.

The second movement box (Fig. 4) allowed the measurement of eccentric and concentric force of a "rolling in and out" a bar with all fingers (except the thumb). The free turning bar was mounted on a gliding sled on the inner side of the box. An anatomically shaped handle, which was grasped by the thumb and thenar acted as a resistance bearing against the flexion movement. The movement in the fingers started by flexion of the distal interphalangeal (DIP) and the proximal interphalangeal (PIP) joints almost continuously until they were in contact with the bar. Slight flexion of the metacarpophalangeal (MCP) joints finished the rolling movement. Linear range of motion of the bar was 40 mm. This movement was designed to allow some movement in the interphalangeal joints (flexion up to 40°) and therefore a certain amount of tendon gliding to obtain a theoretical moderate amount of friction between the pulleys of the finger and the flexor tendon.

The third movement box (Fig. 5) allowed the measurement of only isolated eccentric and concentric flexion moment of the PIP joint. The wrist was fixed in a splint in 25° extension, the MCP joint in 30° flexion. The external force acted as a rotational movement at the tip of the third and fourth fingers forcing the DIP joint into hyperextension. Range of motion in the PIP joint was between 60° and 100° flexion where the transmission of force to the A2, A3 and A4 pulleys was most distinct. It was assumed that the greatest friction between pulleys and the flexor tendon became apparent in this position (increase of friction as PIP flexion increases, Zhao et al., 2000).

2.4. Measurement devices

A piezoelectric force transducer (Kistler 9301A SN488642) was connected in series with the cable wires between the device unit and the movement device. The signal was reinforced by a charge amplifier (Kistler Type 5011) and stored by a personal computer supported storage oscilloscope (Voltcraft PCS64i). The accuracy (smallest measuring unit) of the oscilloscope was 0.2 N m/step for wrist flexion, 5 N/step for finger rolling in and out 0.1 N m/step for PIP flexion.

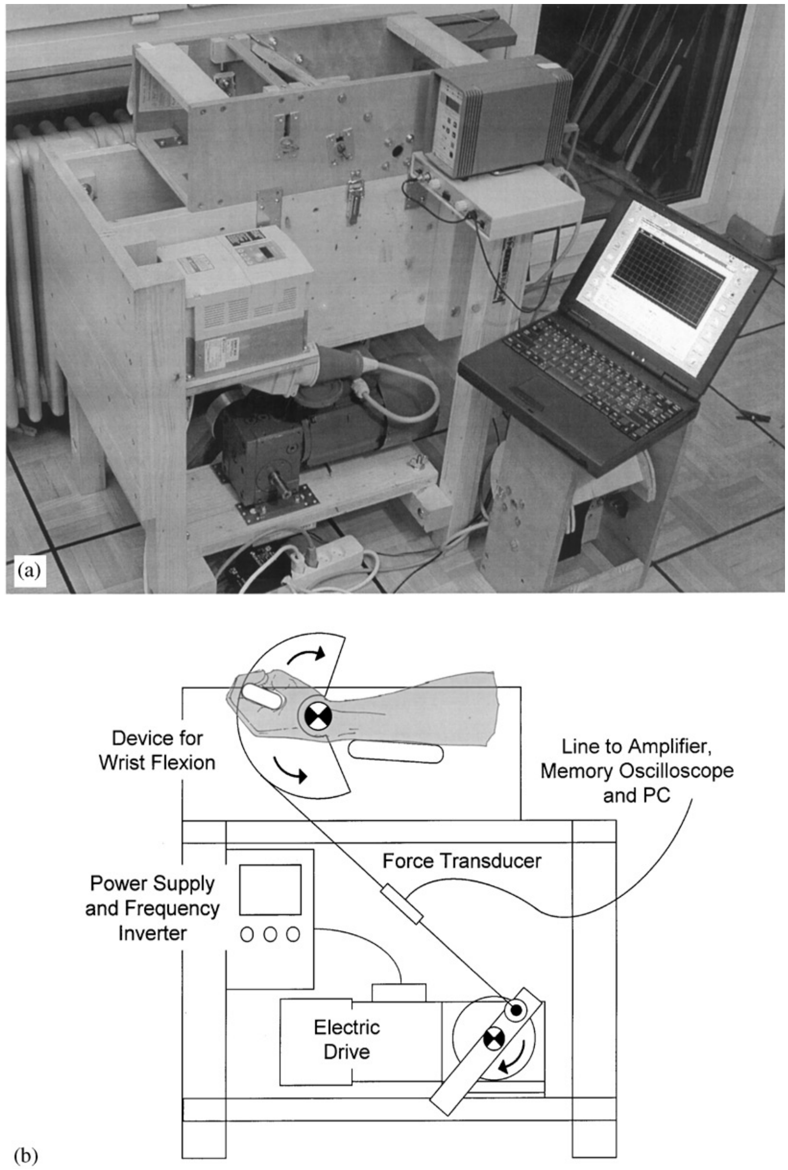

Fig. 2. Isokinetic movement apparatus (a, b) existing of a frame where the electric drive (5), power supply (4) and one of the three movement devices (1) is mounted. A flexible steel cable with a piezoelectric force transducer (3) is connected to the drive (6) allowing an almost sinusoidal reciprocating motion in the movement device. Real time measurement is performed by means of an oscilloscope and a PC (2).

2.5. Measurements

To develop maximum force in a movement using an isokinetic device requires adequate co-ordination. Before each measurement every subject was allowed to adopt to the sinusoid movement of the engine as long as he wished and until he felt confident with the device. This precaution was taken to prevent injuries and to be sure that the subject applied reliable maximum force. An eccentric movement influences the maximum force of the following concentric movement positively (Buehrle et al., 1985) by a elastic recoil mechanism of the muscle. In order to exclude such influences a relatively low speed of movement was chosen (4 s/one complete cycle of concentric and eccentric movement) and the subject was instructed to relieve activity shortly in between the concentric and eccentric movement. At least three consecutive cycles (usually 4–5) of eccentric and concentric movement had to be performed. Frequency of a whole eccentric and concentric cycle was 0.5 Hz for each of the three different devices. The measurements were performed in the following order: (1) wrist flexion, (2) rolling in a bar movement, (3) PIP joint flexion. There was at least 30 min time between each exercise for recovery to exclude a fatigue effect.

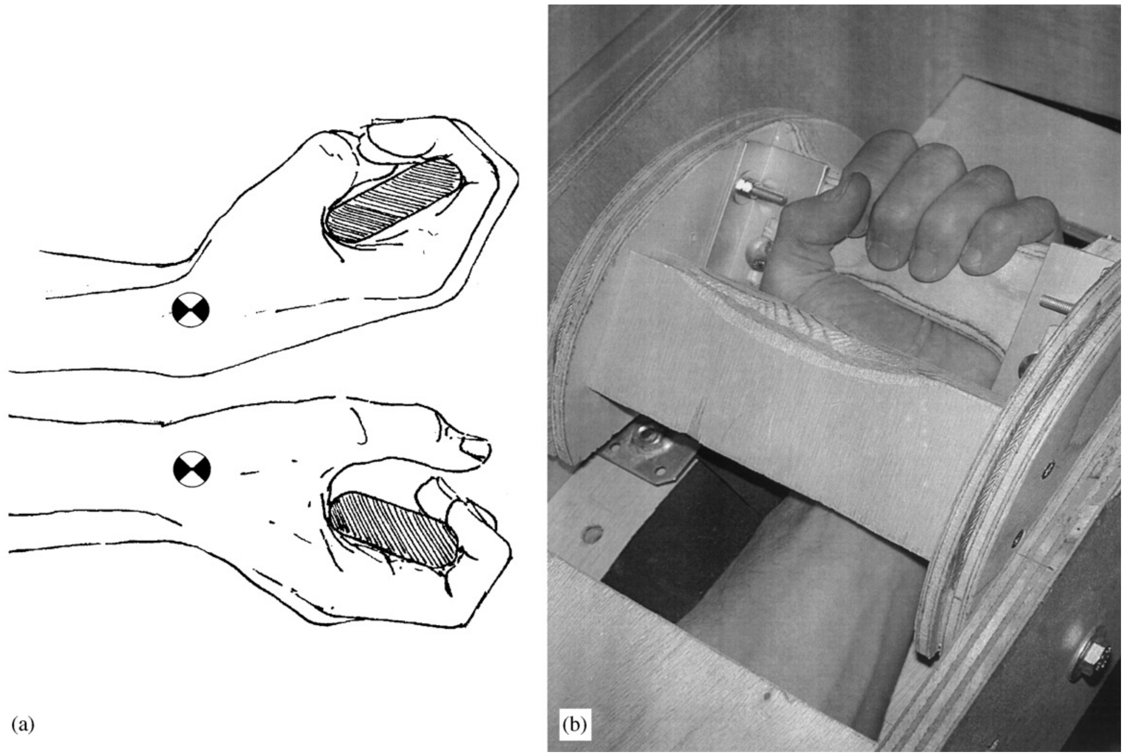

Fig. 3. Wrist flexion device (b) allowed eccentric and concentric flexion of the wrist of 30° on each side (a) of the neutral position (extension and flexion).

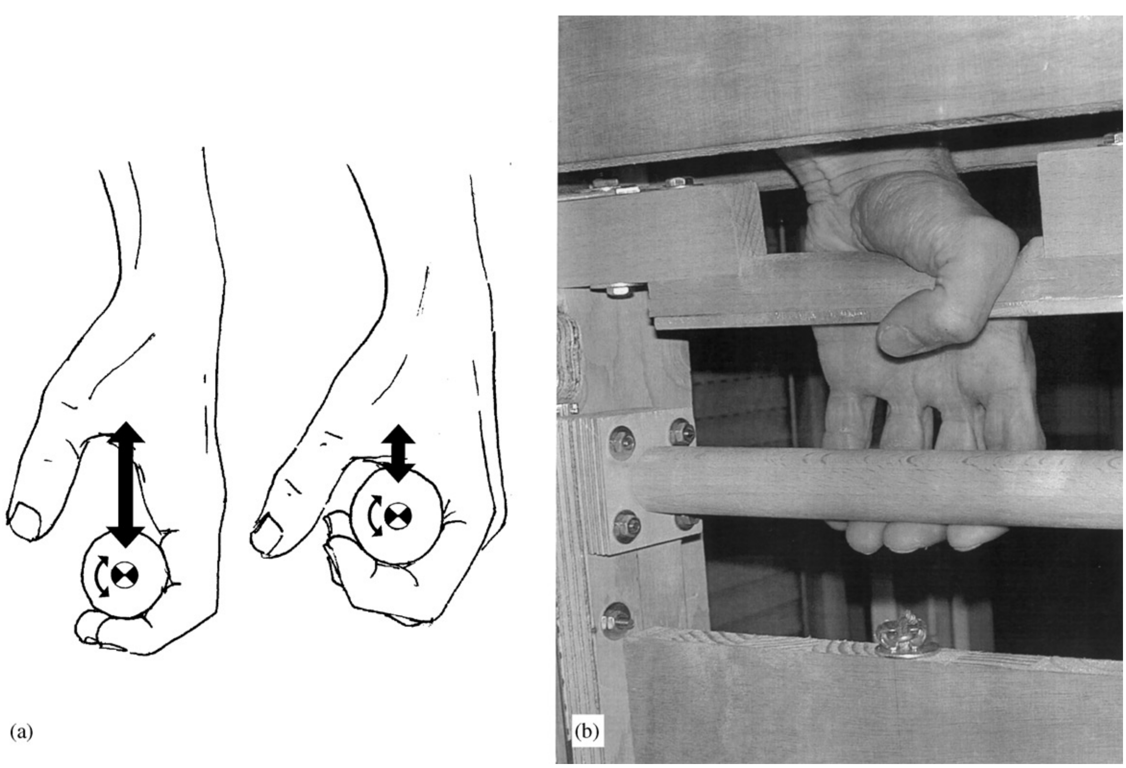

Fig. 4. Device for "rolling in and out a bar" movement (b) allowed eccentric and movement with all fingers (except the thumb) with a range of motion of the interphalangeal joints not more than 40°. The free turning bar was mounted on a gliding sled. An anatomically shaped handle, which was grasped by the thumb and thenar acted as a resistance against the flexion movement. Linear range of motion of the bar was 40 mm (a).

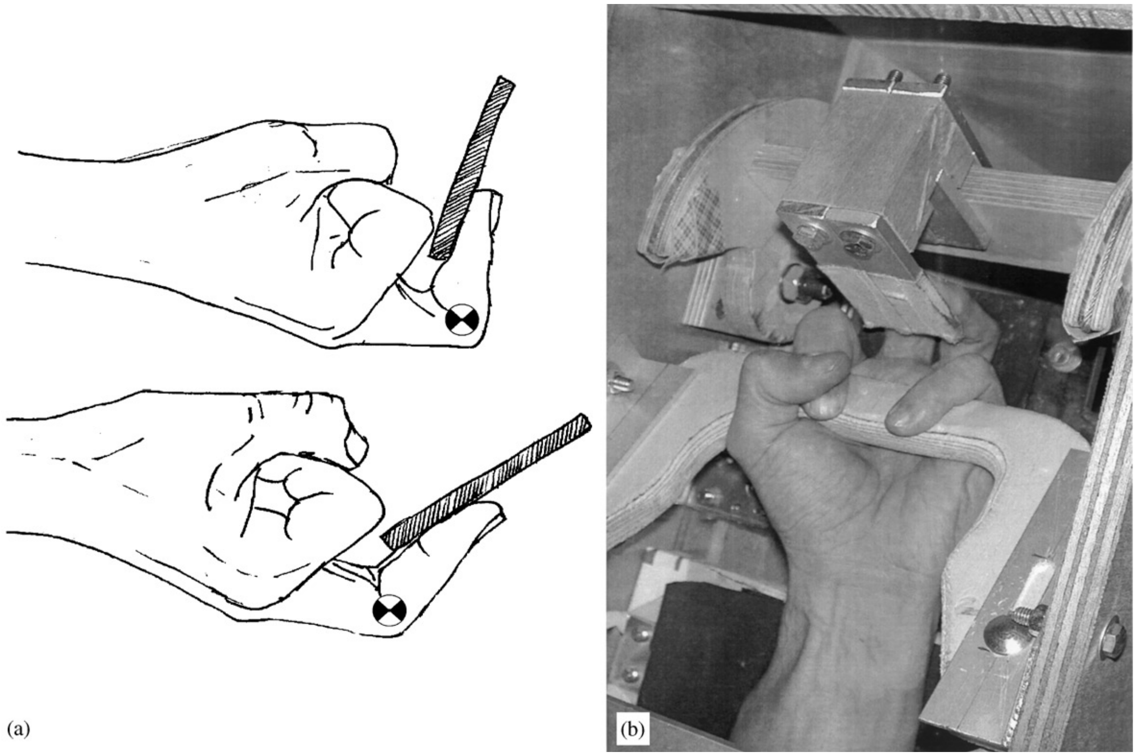

Fig. 5. PIP joint flexion device (b) allowed only isolated eccentric and concentric flexion of the PIP joint of the middle and ring finger. The external force acted as a rotational movement at the tip of the third and fourth fingers forcing the DIP joint into hyperextension. Range of motion in the PIP joint was between 60° and 100° flexion (b).

2.6. Evaluation of accuracy and reproducibility of the measurements

To determine the accuracy and reproducibility of the measurements 48 single measurements in the left and right hand of one of the subjects, distributed over 3 days (to not undergo fatigue) were performed. All measurements with the three devices (wrist flexion, rolling in and out, PIP flexion) were conducted as mentioned above. The results of the measurements with wrist flexion showed a mean, maximum eccentric moment, left side: 19.6 N m (SD 1.6); right side: 21.2 N m (SD 1.5) and concentric moment, left side: 16.7 N m (SD 1.3); right side: 18.1 N m (SD 1.2). Eccentric to concentric strength deficit was 14.6% (SD 4.3) for the left and 14.6% (SD 3.0) for the right side. The corresponding results for finger rolling were eccentric force, left side: 508 N (SD 22), right side: 508 N (SD 34), and concentric force, left side: 393 N (SD 31), right side: 392 (SD 34); strength deficit, left side: 22.6% (SD 4.3) and right side: 22.7% (SD 4.3). The results for PIP flexion were eccentric moment, left side: 10.6 N m (SD 0.7) and right side: 11.4 N m (SD 0.5); and concentric moment, left side: 8.0 N m (SD 0.7), right side: 8.6 N m (SD 0.6); strength deficit was, left side: 24.6% (SD 4.1) and right side: 24.9% (SD 3). All measurements showed an average standard deviation of 7%.

2.7. Data analysis

The values of the three highest peaks of eccentric and the maximum peaks of the three following concentric peaks were chosen for evaluation. The differences of the means of the three eccentric and the three concentric maximum moments (movement 1 and 3) or forces (movement 2) each were expressed as percentages representing force or moment deficit. The force (movement 2) and moment (movement 1 and 3) deficits where compared using the one-way ANOVA test and the two-tailed paired Student *t*-test.

3. Results (Fig. 6)

3.1. Eccentric and concentric wrist flexion

Average maximum moment was 22.6 N m (SD 4.5) for eccentric and 19.1 N m (SD 3.6) for concentric flexion movement. The mean of eccentric to concentric differences was 14.5% (SD 5.9).

3.2. Eccentric and concentric rolling in a bar with the IP joints

Average maximum force was 581 N (SD 100) for eccentric and 430 N (SD 77) for concentric flexion

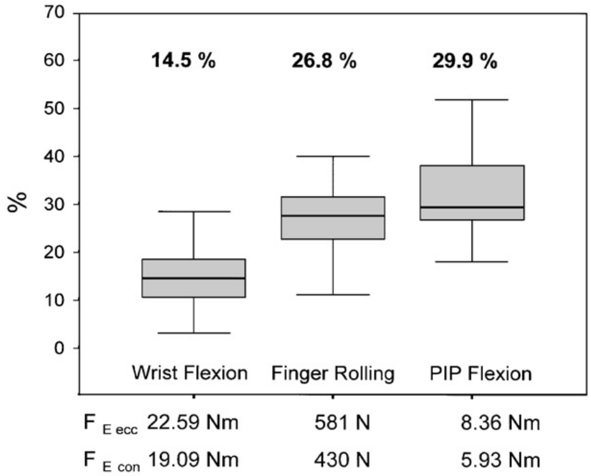

Fig. 6. Force deficits (difference between eccentric and concentric maximum forces or moments expressed in percentages) of the three different movement devices (boxplot indicating quartiles and median).

movement. The mean of eccentric to concentric differences in percentage was 26.8% (SD 7.4).

3.3. Eccentric and concentric PIP joint flexion

Average maximum moment was 8.36 N m (SD 2.33) for eccentric and 5.93 N m (SD 1.69) for concentric flexion movement. The mean of eccentric to concentric differences was 29.9% (SD 6.8).

3.4. Comparison of the eccentric to concentric maximum force differences (strength deficit) of the three different movements

The eccentric to concentric difference of force (strength deficit in %) was most distinct in the PIP joint flexion (29.9%). It was statistically significant less in the rolling in a bar movement (26.8%) ($p<0.001$) and in the wrist flexion movement (14.5%) ($p<0.001$) (Fig. 6).

3.5. Coefficient of friction

The coefficient of friction according to Eq. (10) was $\mu = 0.075$ (± 0.021).

4. Discussion

4.1. Friction in the tendon–pulley interface

Friction between pulleys and flexor tendons has been differently investigated until now. The most important reason for this was to assess friction after trauma (Lane et al., 1976) and friction of different suture techniques and tendon grafts (Peterson et al., 1986; Woo et al., 1981; Uchiyama et al., 1997; Coert et al., 1995; Williams and Amis, 1995; Nishida et al., 1998). Therefore, various indirect measurement techniques and models (Fowler and Nicol, 2000) and measurements in animals have been described (Lane et al., 1976). Moro-oka et al. (1999) measured in vitro friction in rabbits and found that the friction coefficient was not affected by the load (only up to 2 N) but by the preloading time. Uchiyama et al. (1995) and An et al. (1993) developed a method to measure friction in vitro only between the human A2 pulley and a tendon and determined friction coefficient to be 0.004 ± 0.014. They suggested that friction is significantly higher than in diarthrodial joints. Goldstein et al. (1987) showed that static strain differences of flexor tendons over the wrist increased during flexion and extension of 65° compared to the neutral position. This indicates that friction is apparent during tendon and tendon sheath interaction. However, until now there are only few who investigated forces in vivo. Schuind et al. (1992) measured the tendon forces intraoperatively during different activities. During passive mobilisation (extension–flexion PIP joint) of the index finger they found forces up to 0.3 kg (flexor digitorum profundus, FDP) and during active unresisted flexion up to 1.9 kg (flexor digitorum superficialis, FDS). During active unresisted DIP flexion they found FDP forces up to 2.9 kg. However, this increase may be due to co-contraction of the extensor tendons during the voluntary flexion of the PIP joint. The forces which were necessary to just move a finger passively represent the amount of friction in the flexor tendon sheath, soft tissue and joints. Friction force coefficient in joints are low ($\mu = 0.002-004$; Moore et al., 1991) even during high load. The friction in the soft tissue and skin is very likely to remain the same during high load. Therefore, it is likely that friction between flexor tendons and pulleys is mostly responsible for the increase of the difference between eccentric and concentric maximum force during PIP joint flexion as it was found in this study. The force of friction can be quantified according to Eq. (8) to be 40.1 N (SD 11.4) based on the results of measurements. Friction therefore is responsible for 9.1% (SD 2.6) of the maximum possible eccentric flexion force in the PIP joint. Coefficient of friction (μ) can be estimated by Eq. (10) to be 0.075 (± 0.021). It seems that such high amount of friction only occurs during high load or compression between pulley and flexor tendons. High compression forces were measured directly and found to be three times as high over the distal edge of the A2 pulley (PIP 90° flexed) compared with the external force at the tip of the finger (Schweizer, 2001).

During rock climbing using the crimp grip position, forces up to 180 N occur at the fingertips and imply a theoretical force of the flexor tendons acting to the A2 pulley of 400–800 N. This is close to or even beyond its maximum force (407 N by Lin et al., 1990; 375 N by Tang, 1995; 18.3 kg by Manske and Lesker, 1977).

Friction during the crimp grip position may occur along the whole A1 and A2 pulley and the wrist, because the flexor tendons glide in these areas. However, according to Uchiyama et al. (1995), friction is apparently most distinct at the angulation of the distal edge of the A2 pulley.

4.2. Eccentric and concentric maximum force

The differences between eccentric and concentric maximum force (strength deficit) is due to an increased stimulus of the delta fibres (stretching reflex) and due to the elastic properties of the muscles. Its extent during slow motion depends mostly on the state of training of the concerning muscle (Schmidtbleicher and Buehrle, 1980). Strength deficit lessens as an athlete's muscles become trained, reaching around 5%. It is known to differ from 5% to 45% (100% corresponds to maximum eccentric force) in different individuals (Schmidtbleicher and Buehrle, 1980) and it is also of important diagnostic value in exercise physiology (Buehrle et al., 1985). The method which was developed in this study may therefore be of value in determining strength deficit of the wrist and finger flexors.

4.3. Analogy to the TLM of chiropterans

Bats, some mammalians and birds may dangle on their digits without muscular contraction. The mechanism sustains flexion by interlocking the flexor tendon with the corresponding pulleys. They may hang all night long, during hibernation or still after they have died. Schaffer (1905) was the first to describe a "Sperr-Hemmvorrichtung" in bats where the flexor tendon interacts and locks with the fibrous tendon sheath. Schutt (1993) investigated the mechanism more precisely in bats and Quinn and Baumel (1993) finally called it TLM and compared it in different bat species (chiropterans). A similar mechanism was described in climbing mammals by Schaffer (1905) and Haffner (1996), in birds by Quinn and Baumel (1990) and in dermoptera by Simmons and Quinn (1994). The digits of most bats consist of three phalanges and a conjoint tendon instead of a FDP and a FDS tendon. The conjoint tendon inserts at the terminal ungual phalanx after running through the flexor tendon sheath consisting of an fibro-osseous A2 pulley like part over the proximal phalanx. The TLM in bats consists of tubercles on the volar side of the conjoint tendon and of transverse plicae at the inner surface of the pulley. As the flexor muscle is activated it pulls the conjoint tendon away from the bone (bowstringing) and interlocks the plicae against the tubercles. The friction between tendon and pulley is that high that flexor muscle may completely relax. Unlocking is enabled by unloading the finger and by two elastic ligaments the one extending the DIP joint and the other pulling the conjoint tendon distally (Quinn and Baumel, 1993).

4.4. Friction between flexor tendons and pulleys

Walbeehm and McGrouther (1995) compared the TLM with the anatomy and function of the human flexor tendon sheath and described a tendon compressing mechanism (TCM) where the FDP tendon is compressed circularly by the chiasma of the FDS tendon and the A2 pulley. They found, using an electron microscope, transverse ridges on the inner surface of the A2 pulley and on the volar surface of the FDP tendon. Direction of the fibres of the two gliding partners demonstrated a preferential direction for friction because the shape of the tendon and the direction of the fibres changed when the tendon was under tension. In flexion movement the friction would be less but as soon as the system became static, or eccentric, the directional angle of the fibres changed to favour friction. The chiasma of the FDS tendon was described also (Shrewsbury and Kuczinsky, 1974; Walbeehm and McGrouther (1995)) to increase friction and to partially lock the FDP tendon by acting like a Chinese finger trap. They hypothesised that friction may be an important normal functional mechanism of the flexor tendon sheath during power grip.

The results of this study support the mechanism of a TLM and a TCM. The difference of eccentric to concentric maximum force being much more distinct for the PIP flexion (29.9%) than to the wrist flexion (vs. 14.5%) or rolling movement indicates that frictional force in this movement is present. Comparison of the friction coefficient of the PIP flexion ($\mu = 0.075 \pm 0.021$) during high load with the results of Uchiyama et al. (1995) who measured friction of the tendon pulley interface with low load (4.9 N), (friction coefficient $\mu = 0.04 \pm 0.014$) indicates also that significantly higher friction is apparent during high load flexion movement. However, it has to be considered that Uchiyama measured friction only at the A2 pulley whereas during PIP flexion in this study at least the A1, A2 and the A3 pulley was involved. Friction may therefore be of significant importance during power grip and represents a biomechanical function.

4.5. Injury mechanism of the A2 pulley in rock climbers

During rock climbing, the A2 pulley and the A4 pulley are stressed in a way that injuries and overuse are very common (Bollen, 1990; Cartier et al., 1985; Gabl et al., 1998; Tropet et al., 1990). Foremost the so-called crimp grip position where the PIP joint is flexed 90° or more and the DIP joint is hyperextended results in a distinct bowstringing (Schweizer, 2001) and stresses the distal edge of the A2 pulley mostly. Zhao et al. (2000)

showed that gliding resistance of the flexor tendon increased as the PIP joint angle increased. This and the results of the present study support the hypothesis of high friction in the crimp grip position or during a flexed PIP joint. Friction may be an advantage for rock climbers. It may support the holding force of their flexor muscles but on the other hand may also increase the susceptibility to injury. When feet abruptly come off the rock the fingers experience a sudden increase of load and friction which may lead to injury of the flexor tendon pulleys. Injury mechanism therefore is not only due to the bowstringing effect but also due to high friction in near-static high load.

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