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THE CONTROLLABILITY OF THE UNLOADED HUMAN FINGER WITH SUPERFICIAL OR DEEP FLEXOR

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Abstract—The unloaded human finger with a taut deep flexor functions as a bi-articular chain, because the angulations of the distal two joints are mechanically coupled. In this chain two flexors exist: the superficial and deep flexor. However, for elementary control of the unloaded finger, only one flexor is required. This puts forward the question of which flexor is most suited for unloaded finger control. In the present paper it is argued that due to the chiasma tendinum and the coupled rotations of the distal two joints, the deep flexor is anatomically better positioned than the superficial flexor for optimal unloaded finger control. © 1997 Elsevier Science Ltd. All rights reserved

Keywords: Finger control; Flexor digitorum profundus; Flexor digitorum superficialis; Swanneck deformity; Musician.

NOMENCLATURE

MCP, PIP, DIP	metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joint
MCP, IP	first and second joint in the bi-articular model
P	flexor digitorum profundus
S	flexor digitorum superficialis
E	extensor digitorum
I	interosseus
M	medial insertion of extensor assembly
T	terminal insertion of extensor assembly
F_i	force in tendon i ($i = P, S, E, I, M, T$)
r_{ij}	moment arms of the tendons over the resp. joints. The first index denotes the motor: P, S, E, I, M, T. The second index indicates the joint.
r_{ij}^*	equivalent moment arm in bi-articular chain
$\mathbf{R}_i$	moment arm vector of motor i, defined by the Cartesian coordinates: $(\pm r_{i1}, \pm r_{i2})$
$[\mathbf{R}_i \times \mathbf{R}_j] = [(\pm r_{i1})(\pm r_{j2}) - (\pm r_{i2})(\pm r_{j1})]$	the value of the vector product of the vectors $\mathbf{R}_i, \mathbf{R}_j$
Greek letters	
θ_j	angle of joint j (1, 2, 3: MCP, PIP, DIP)
θ_{2PS}	smallest PIP angle for which $A(T, P_d)$, $A(P^*, E) > A(S, E)$ (definition $A(i, j)$ in expression (7))

INTRODUCTION

The human finger, modelled in Fig. 1(a), presents two striking anatomical constructs, of which the significance is not immediately obvious. (i) One is the crossing of the flexor tendons between the first and second joint. This crossing is anatomically realised by the chiasma tendinum in the superficial flexor tendon S. Through this chiasma the deep flexor P perforates the superficial flexor tendon from a deep course at the MCP joint to a superficial course at the PIP joint. (ii) The other is that distal to the MCP joint the extensor assembly dissociates into what are further called the medial and terminal slips, which insert in the base of the middle and distal phalanx, respectively. The effect of these distinct insertions is that when the deep flexor, and the medial and the terminal slips are taut, the PIP and DIP joints rotate as a mechanism with one degree of freedom (Landsmeer, 1958; Leijnse *et al.*, 1992; Spoor and Landsmeer, 1976). With this mechanism active, the unloaded finger in the sagittal plane has only two degrees of freedom. The PIP–DIP mechanism can be formally replaced by a single joint, further called the IP joint (Spoor and Landsmeer, 1976), which allows to study the unloaded three joint finger as a biarticular chain [Fig. 1(b)]. The resulting bi-articular MCP–IP model is equivalent to the unloaded three-joint model, in the sense that the equilibrium forces in the tendons in both models are in proportion, and that equal tendon displacements cause MCP–IP rotations in the biarticular model equal to the MCP–PIP rotations in the three-joint model with active coupling mechanism. In the MCP–IP model four motors are present. However, for the complete control of a bi-articular chain three motors suffice (more precisely: when the bi-articular chain can be controlled by four or more motors, three of these motors can control the chain by themselves) (Landsmeer, 1955; Leijnse, 1996). Therefore, when the model of Fig. 1(b) is controllable, one of the four motors is redundant. With certain conditions on the moment arms of the motors, which are satisfied in the normal finger, either the flexor P or S may be inactive while the chain remains controllable (Landsmeer, 1955; Leijnse and Kalker, 1995; Spoor, 1983). This leads to the question further investigated: assuming their mutual redundancy, which of the two flexors is most adapted for control of the unloaded finger? It is further argued that the deep flexor is structurally superior to the superficial flexor in unloaded control, and that this predisposition increases with the crossing angle of their tendons in the bi-articular model of Fig. 1(b). This crossing angle finds its cause in both the chiasma tendinum and the PIP–DIP coupling mechanism, which means that these anatomic constructions obtain a further biomechanical significance. The

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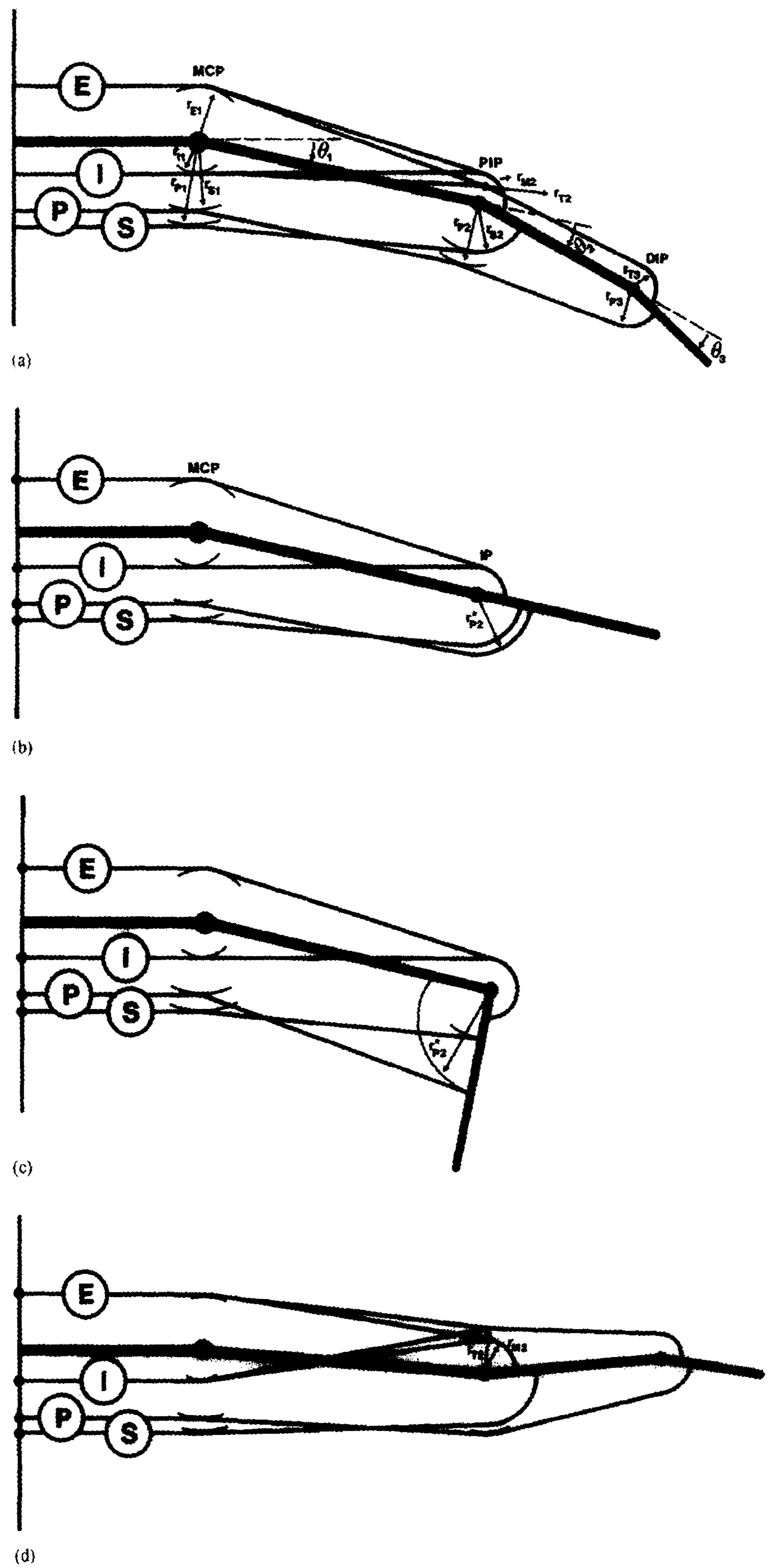

Fig. 1. (a) Two dimensional model of the finger. (b) Bi-articular equivalent finger model with extended IP joint. (c) Bi-articular equivalent finger model with flexed IP joint. (d) Three-articular finger model with hyperextended PIP and bowstringing terminal extensor slip ($r_{M2} < r_{T2}$).

arguments are based on the concepts about the controllability of bi-articular chains introduced in Leijnse (1996). Some clinical applications are briefly discussed, such as the controllability of fingers prone to swanneck deformities; the relative contribution of the flexors to the claw-hand deformity in the case of intrinsic paralysis; and the importance of the good functioning of the coupling mechanism in fast finger movements, as in the playing of a musical instrument.

MATERIAL AND METHODS

The bi-articular force model of the human finger

The model further investigated consists of the torque equilibrium equations of the massless unloaded finger model of Fig. 1(a) (from Spoor, 1983):

$$r_{E1} \cdot F_E - r_{I1} \cdot F_I - r_{S1} \cdot F_S - r_{P1} \cdot F_P = 0, \quad (1a)$$

$$r_{M2} \cdot F_M + r_{T2} \cdot F_T - r_{S2} \cdot F_S - r_{P2} \cdot F_P = 0, \quad (1b)$$

$$r_{T3} \cdot F_T - r_{P3} \cdot F_P = 0, \quad (1c)$$

$$F_T + F_M - F_E - F_I = 0, \quad (1d)$$

$$F_E, F_I, F_S, F_P, F_T, F_M \geqslant 0. \quad (1e)$$

in which the forces are: F_E: the extensor, F_S: superficial flexor, F_P: deep flexor, F_I: interosseus, F_M and F_T: medial and terminal slips of the extensor assembly. Moment arms of extension and flexion are taken positive and negative, respectively, and are noted with explicit sign. Joint angles are further assumed positive for flexion from the extended position, and negative for hyperextension. Finger positions with the joints in end positions (taut volar plates) are not considered. For reasons of simplicity the lumbrical muscle is ommitted from the model, as its inclusion would not influence the present arguments. The elimination of F_M and F_T results in the equilibrium equations of the equivalent bi-articular MCP-IP model of Fig. 1(b):

$$F_E \cdot \begin{bmatrix} r_{E1} \\ r_{M2} \end{bmatrix} + F_I \cdot \begin{bmatrix} -r_{I1} \\ r_{M2} \end{bmatrix} + F_S \cdot \begin{bmatrix} -r_{S1} \\ -r_{S2} \end{bmatrix} + F_P \cdot \begin{bmatrix} -r_{P1} \\ -r^*_{P2} \end{bmatrix} = 0. \quad (2)$$

This equation is valid only when the positivity conditions $F_T, F_M \geqslant 0$ are satisfied. $F_T \geqslant 0$ when $F_P \geqslant 0$; when $F_P = 0$, equation (2) describes MCP–PIP equilibrium only. $F_M \geqslant 0$ when

$$F_M = \frac{1}{r_{M2} r_{T3}} [r_{P2} r_{T3} - r_{P3} r_{T2}] \cdot F_P + \frac{r_{S2}}{r_{M2}} \cdot F_S \geqslant 0. \quad (3)$$

The equivalent moment arm r^*_{P2} of the deep flexor P at the equivalent IP joint is given by (Spoor and Landsmeer, 1976):

$$r^*_{P2} = r_{P2} + \frac{r_{P3}}{r_{T3}} \cdot (r_{M2} - r_{T2}). \quad (4)$$

In the human finger the terminal slips of the extensor assembly at the PIP are free to bowstring palmarly with PIP flexion (r_{T2} decreases), and also to a certain extent dorsally with PIP hyperextension [Fig. 1(d)], at which $r_{T2} > r_{M2}$. This change in the moment arm of the terminal slip at the PIP with PIP flexion is the basis of the coupled movement of the PIP and DIP joints. In the following $r_{T2}(\theta_2)$ is approximated as (Leijnse and Kalker, 1995)

$$r_{T2} = r_{M2} \left[1 - \frac{2\theta_2}{(\pi/2)} + \frac{\theta_2^2}{(\pi/2)^2} \right]. \quad (5)$$

Expression (4) shows that when r_{T2} decreases, the equivalent moment arm r^*_{P2} increases. The relationships (4) and (5) are represented in Fig. 2(a), while in Figs 1(b) and (c) the equivalent deep flexor moment arms r^*_{P2} for the flexed and extended IP joint, respectively, are drawn in proportion.

The moment arm vector diagram of the equivalent bi-articular chain

Equation (2) can be represented as a vector diagram, further called the *moment arm vector diagram* (Leijnse,

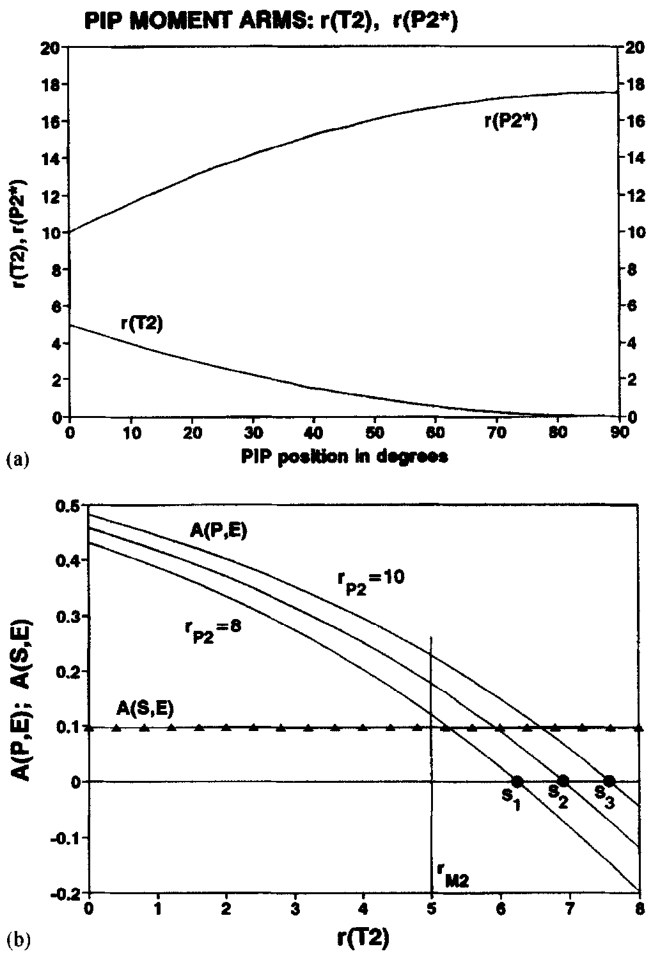

Fig. 2. (a) Moment arm of the terminal extensor slip $[r(T2)]$ at the PIP and equivalent IP moment arm of deep flexor $[r(P2^*)]$ as a function of the PIP angle. (b) Antagonism $A(P, E)$ of the extensor and deep flexor, and antagonism $A(S, E)$ of extensor and superficial flexor, as a function of the changes in the moment arm of the lateral band with the PIP position. $r_{T2} = 0$ mm: PIP near full flexion. $r_{T2} = 5$ mm: PIP in extension ($\theta_2 = 0, r_{T2} = r_{M2}$). $r_{T2} > 5$ mm: PIP in hyperextension ($\theta_2 < 0, r_{T2} > r_{M2}$). $A(S, E)$ is constant, as all moment arms involved are assumed constant. $A(P, E)$ decreases with increasing r_{T2}. The three $A(P, E)$ curves correspond with the anatomic moment arms $|r_{P2}| = 8, 9, 10$ mm, respectively. s_1, s_2, s_3 are moment arms r_{T2} at which the finger with the (P, E, I) motor triplet becomes unbalanced with $|r_{P2}| = 8, 9, 10$ mm, respectively.

1996), by assuming that the column arrays of moment arms are the Cartesian coordinates ($\pm r_{i1}$, $\pm r_{i2}$) (positive signs for extension moment arms) of what is further called the *moment arm vectors* $\mathbf{R}_i$ of the motors *i*:

$$F_E \cdot \mathbf{R}_E + F_I \cdot \mathbf{R}_I + F_S \cdot \mathbf{R}_S + F_P \cdot \mathbf{R}_P^* = 0. \qquad (6)$$

The bi-articular chain is in equilibrium when the moment arm vectors $\mathbf{R}_i$, multiplied by the appropriate non-negative motor forces F_i, balance out. The moment arm vector diagrams of the equivalent bi-articular chains of the Figs 1(b) and (c) are given in the Fig. 3, using the moment arm values of Table 1.

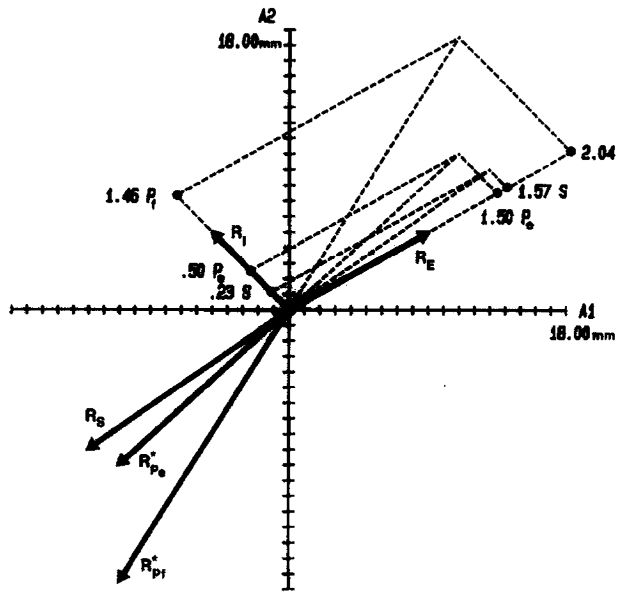

Fig. 3. Moment arm vector diagram of the equivalent bi-articular model. At the horizontal axis (A1) the individual moment arms r_{i1} of the finger tendons at the MCP joint are noted; at the vertical axis (A2) the (equivalent) moment arms r_{i2}^* of the finger tendons at the PIP joint. $\mathbf{R}_E$, $\mathbf{R}_I$, $\mathbf{R}_S$ are the moment arm vectors of extensor, interosseus and superficial flexor. $\mathbf{R}_{Pe}^*$, $\mathbf{R}_{Pf}^*$ are the moment arm vectors of the deep flexor with extended and flexed IP joint, resp. The forces in extensor and interosseus as a function of the flexor forces can be determined by the force parallelograms, as follows. Given a force *F* in a flexor (1 N in the figure), the force in *E* or *I* is equal to this flexor force *F* multiplied by the length of the projection (by the parallelogram construction) of the negative moment arm vector of the flexor on the moment arm vector of *E* or *I*, divided by the total length of the moment arm vector of *E* or *I* (in other words, the factors by which the moment arm vectors of *E* and *I* must be multiplied to balance the negative moment arm vector of the flexor, times *F*). In the figure, three situations are represented. (i) $F_S = S$ ($= 1$ *N*), $F_P = 0$, which results in: $F_E = 1.57S$, $F_I = 0.23S$; (ii) $F_S = 0$, $F_P = P_e$ ($= 1$ N) (extended IP joint): $F_E = 1.5P_e$, $F_I = 0.5P_e$; (iii) $F_S = 0$, $F_P = P_f$ ($= 1$ N) (flexed IP joint): $F_E = 2.04P_f$, $F_I = 1.46P_f$.

Table 1. Moment arms of the motors (in mm). From: Spoor (1983)

	Moment arm			Value		
Motor	MCP	PIP	DIP	MCP	PIP	DIP
P	r_{P1}	r_{P2}	r_{P3}	11	10	6
S	r_{S1}	r_{S2}	—	13	9	—
E	r_{E1}	r_{M2}	r_{T3}	9	5	4
I	r_{I1}	r_{M2}	—	6	5	—

Note. r_{T3}: function of PIP position

Exact antagonism; good controllability of the bi-articular chain

From Leijnse (1996), some definitions and properties of the bi-articular chain are repeated without further comment.

(i) Two motors M_i and M_j are called *exact antagonists* when their moment arm vectors are exactly opposite: $\mathbf{R}_i = \alpha \cdot \mathbf{R}_j$, $\alpha < 0$. When $\alpha > 0$ (collinear moment arm vectors of the same sense), the motors are called *exact agonists*.

(ii) The three-tendon bi-articular chain is *controllable* when the moment arm vectors can balance out when multiplied by appropriate *strictly* positive scalars. This requires that no motors are exact agonists or antagonists ($\mathbf{R}_i \neq \alpha \cdot \mathbf{R}_j$).

(iii) The three-tendon bi-articular chain is *well controllable* when it is controllable, and when no motors are too antagonistic/agonistic. For further use, the *degree of antagonism* $A(M_i, M_j)$ is defined as

$$A(M_i, M_j) = \frac{[\mathbf{R}_i \times \mathbf{R}_j]}{\|\mathbf{R}_i\| \, \|\mathbf{R}_j\|} = \sin \beta_{ij}, \qquad (7)$$

i.e. the sine of the counterclockwise angle β_{ij} between the vectors $\mathbf{R}_i$ and $\mathbf{R}_j$. This function is not uniquely defined since vectors at angles of $\pi/2 \pm \beta_{ij}$ have the same value. With $\pi/2 < |\beta_{ij}| < \pi$ and $0 < |\beta_{ij}| < \pi/2$, the motors are defined as antagonists and agonists, respectively. With $\beta_{ij} = 0$ and $\beta_{ij} = \pi$ the motors are exact agonists and antagonists, resp. When $\beta_{ij} = \pi/2$, the moment arm vectors are orthogonal, and the motors are neither antagonists, nor agonists. When $0 < \beta_{ij} < \pi$, $A(M_i, M_j) > 0$; conversely, when $0 < -\beta_{ij} < \pi$, $A(M_i, M_j) < 0$. It further holds that $A(M_i, M_j) = -A(M_j, M_i)$.

The problem

In Leijnse (1996) it was shown that the three-tendon bi-articular chain is fully controllable when the following conditions on the moment arms of the motors are satisfied (with *F* symbolising a non-specified flexor):

$$A(E, I) \cdot A(I, F) > 0, \quad A(I, F) \cdot A(F, E) > 0. \qquad (8)$$

In the MCP-IP model of the human finger, as represented by the moment arm vector diagram of Fig. 3(a), four tendons are present. When the conditions (8) are satisfied for both flexors (with $F = S$ or $F = P$), the bi-articular model can be controlled by either motor triplet (*S*, *E*, *I*) or (*P*, *E*, *I*). From the above definitions follows that best suited for the control of an unloaded bi-articular chain is the motor triplet of which the motors are least antagonistic to each other. Because of the above established model equivalence, when condition (3) holds this result also applies to the unloaded three-joint model of Fig. 1(a). Hereby it must be noted that in the three-joint model the (*S*, *E*, *I*) triplet only controls the MCP and PIP joints; while the (*P*, *E*, *I*) triplet controls the MCP, PIP, and DIP joints, with the PIP and DIP articulating as an IP joint mechanism. Therefore, 'finger control' further means MCP–PIP control with (*E*, *I*, *S*), and MCP–IP control with (*P*, *E*, *I*). From Fig. 3, based on the normal moment arm values of Table 1, it can be verified that the interosseus is quasi-orthogonal to all other motors:

$$A(I, P^*) \approx 1, \quad A(I, S) \approx 1, \quad A(E, I) \approx 1. \qquad (9)$$

This means that the terms involving the interosseus in expression (8) are non-critical conditions of control. In contrast, the antagonism between the extensor and either flexor is pronounced, and critically determines the controllability of the chain. With the expressions (9) and (3), the conditions (8) are satisfied for $F = S$ when:

$$A(S, E) > 0 \quad (\Leftrightarrow r_{E1} r_{S2} - r_{M2} r_{S1} > 0) \tag{10}$$

and for $F = P$ when

$$A(P^*, E) > 0 \quad (\Leftrightarrow r^*_{P2} r_{E1} - r_{P1} r_{M2} > 0), \tag{11a}$$

$$A(T, P_d) > 0 \quad (\Leftrightarrow r_{P2} r_{T3} - r_{P3} r_{T2} > 0). \tag{11b}$$

$A(T, P_d) > 0$ (in which $\mathbf{R}_T = (r_{T2}, r_{T3})$, $\mathbf{R}_{Pd} = -(r_{P2}, r_{P3})$) is condition (3) that the DIP–PIP mechanism functions properly {$[\mathbf{R}_T \times \mathbf{R}_{Pd}]$ [expression (7)] is the term between brackets in expression (3)}. By definition, the greater the inequalities (10) or (11), the better the chain is controllable with the respective flexor.

MODEL RESULTS

The differences in the antagonism of the flexors P and S with respect to the extensor E in the equivalent MCP–IP model

With the normal moment arm values of Table 1, the following holds:

(i) The flexor S and the extensor E are almost exact antagonists (see Fig. 3). Therefore, the (E, I, S) motor triplet is not geared for good MCP–PIP control.

(ii) $A(T, P_d)$ and $A(P^*, E)$ in expression (11), and therefore the controllability of the finger by the (P, E, I) motor triplet, increase with PIP flexion, because $r_{T2}(\theta_2)$ decreases. In the real finger the flexor pulleys allow for some bowstringing of the flexor tendons with joint flexion, but this is not comparable to the structural subluxation of the terminal slips T at the PIP, so $A(S, E)$ can modelwise be assumed constant. Since $A(S, E)$ is small, with increasing PIP flexion a situation will be reached in which both $A(T, P_d)$, $A(P^*, E) > A(S, E)$, i.e. with the finger better controllable by the (P, E, I) triplet than by the (S, E, I) triplet. For the values of Table 1, $A(P^*, E) > A(S, E)$ already holds with extended PIP ($\theta_2 = 0$, at which $r_{M2} = r_{T2}$), because $r_{P1} < r_{S1}$. This is visually illustrated in Fig. 3, where $\mathbf{R}_P$ is drawn for the extended PIP ($\theta_2 = 0$, moment arm vector $\mathbf{R}^*_{Pe}$), and the completely flexed PIP ($\theta_2 = 90°$, moment arm vector $\mathbf{R}^*_{Pf}$). In Fig. 2(b) the antagonisms $A(P^*, E)$ and $A(S, E)$ are presented as a function of the changes in r_{T2} with the PIP position, as given in Fig. 2(a).

(iii) In the human finger the terminal slips of the extensor assembly at the PIP may bowstring dorsally when the PIP hyperextends. Since the medial slip of the extensor assembly is prevented from dorsal bowstringing by its insertion in the second phalanx, a situation with $r_{T2} > r_{M2}$, in which $r^*_{P2} < r_{P2}$, may well occur [Fig. 1(d)]. Define θ_{2PS} as the smallest PIP angle for which both $A(P^*, E)$, $A(T, P_d) > A(S, E)$. Then, for all PIP positions with $\theta_2 < \theta_{2PS}$, the finger is better controllable by the (S, E, I) triplet.

(iv) With sufficient dorsal bowstringing of the terminal slip, the sign of one or both the conditions (11) will reverse. In that case the finger with the (P, E, I) motor triplet becomes uncontrollable, and will collapse into a swanneck deformity. For this the amount of bowstringing of the lateral bands need not be large. For instance, for the values r_{P1}, r_{E1} and r_{M2} of Table 1, and the moment arm values $r_{P2} = 8, 9$ or 10 mm, the finger will uncontrollably collapse according to the condition (11b) when $r_{M2} - r_{T2} < -0.3, -1, -1.6$ mm; and according to the condition (11a) when: $r_{M2} - r_{T2} < -1.25, -1.9$ or -2.6 mm, respectively [Fig. 2(b)]. The extreme sensitivity of these conditions to the moment arm lengths is e.g. illustrated by the fact that with $r_{P3} = 5$ mm, the condition (11b) is violated only when $r_{M2} - r_{T2} < -1.4, -2.2, -3$ mm, i.e. more than double of that with $r_{P3} = 6$ mm of Table 1. Expression (11a) further shows that a swanneck deformity may also result from a too large r_{P1} or r_{M2}, or a too small r_{E1}.

(v) With (pathological) variations in the normal moment arm lengths of Table 1, but so that moment arms do not change sign, the expressions (9) still remain positive. However, conditions (10) and (11) may be violated, allowing for the following situations:

$$0 < A(S, E) < A(T, P_d), A(P^*, E), \tag{12a}$$

$$0 < A(T, P_d) \text{ or } A(P^*, E) < A(S, E), \tag{12b}$$

$$A(S, E) < 0 < A(T, P_d), A(P^*, E), \tag{12c}$$

$$A(P^*, E) \text{ or } A(T, P_d) < 0 < A(S, E), \tag{12d}$$

$$A(T, P_d) \text{ or } A(P^*, E), A(S, E) < 0. \tag{12e}$$

Expression (12a) corresponds to the normal finger with the PIP not too extended: the controllability with P is better than with S. In the case of equation (12b) the controllability with S is better than with P. In equation (12c), only the MCP–IP can be controlled, by the triplet (P, E, I). The MCP–PIP cannot be independently controlled; with the (E, I, S) motor triplet and inactive P the MCP–PIP will collapse into a swanneck deformity, in which, however, the DIP remains relaxed. With equation (12d), only the MCP–PIP can be controlled, by the triplet (S, E, I), and the (P, E, I) triplet will provoke a swanneck. In the case of equation (12e) the finger is totally uncontrollable, and will collapse into a swanneck with either of the triplets (P, E, I) and (S, E, I).

(vi) It may be noted that with the increase of r^*_{P2} with PIP flexion, the equilibrium forces in the extensor and interosseus increase relative to the flexor force P. This increase is most pronounced in the interosseus: with the deep flexor and a flexed PIP the interosseus force is almost six times that with the superficial flexor, and about three times that with the deep flexor with extended PIP (Fig. 3). Figure 3 shows that this increase results from two causes: first, an increase in the size of the moment arm vector $\mathbf{R}^*_P$ due to the increase of r^*_{P2}; second, a change in the direction of the moment arm vector $\mathbf{R}^*_P$, which decreases $A(I, P^*)$.

DISCUSSION

From the results (i)–(iii), the following can be concluded for the normal finger.

(i) The three-tendon (S, E, I) bi-articular chain is not optimally controllable, as S and E are too antagonistic (Leijnse, 1996).

(ii) For all sufficiently flexed PIP positions it holds that $A(T, P_d)$, $A(P^*, E) > A(S, E) > 0$, meaning that the finger is better controllable by the (P, E, I) motor triplet than by the (S, E, I) motor triplet.

(iii) The controllability of the finger by the (P, E, I) motor triplet improves with PIP flexion, due to the volar bowstringing of the terminal slips at the PIP.

(iv) In the finger with hyperextended PIP, the controllability by the motor triplet (P, E, I) may become worse than by the (S, E, I) motor triplet, or may even become impossible. This is due to the dorsal bowstringing of the terminal slip at the PIP joint.

Two anatomic constructs which minimize the antagonism of the deep flexor and the extensor

Relative to $A(S, E)$, $A(P, E)$ is structurally increased by the fact that $r_{P1} < r_{S1}$ and $r_{P2} \geqslant r_{S2}$, while also $r^*_{P2} > r_{P2}$, except with PIP hyperextension.

(i) $r_{P1} < r_{S1}$; $r_{P2} \geqslant r_{S2}$: Anatomically, the deep flexor approaches the MCP joint deep into the superficial flexor, and perforates the superficial flexor tendon through the chiasma tendinum to a tract superficial to the superficial flexor at the PIP. Without the chiasma tendinum, the deep flexor would necessarily have to run superficial to the superficial flexor at both the MCP and PIP joints in order to reach the DIP joint (a deep tract being blocked by the then insurpassable insertion of the superficial flexor in the middle phalanx), meaning that less functional differentiation between the deep and superficial flexor would exist.

(ii) *Maximization of* r^*_{P2}: The coupling mechanism results from the insertion of the extensor assembly into both the medial and terminal phalanx, and the fact that the terminal slips at the PIP shift volarly with PIP flexion. The major consequence of this mechanism is that the finger (in the sagittal plane) can be entirely controlled by only three motors: the (P, E, I) triplet. If such mechanism would not exist, the finger would have three independent joints, which require minimally four motors for control (to control n joints in a two-dimensional unloaded chain, $n + 1$ motors are minimally required). In addition to the reduction of the number of motors required for basic finger control, the coupling mechanism also provides the large equivalent moment arm r^*_{P2} of the flexor P, which in the flexed finger (when $r_{M2} > r_{T2}$) is greater than the normal anatomic moment arm r_{P2} of the flexor P [expressions (4) and (5)].

It follows that with respect to the good controllability of the unloaded finger by the (P, E, I) motor triplet, both the chiasma tendinum and the coupling mechanism have a fundamental significance.

The dominance of the deep flexor over the superficial flexor in the control of the unloaded finger

For all positions with the PIP not too-extended ($\theta_2 > \theta_{2PS}$), the unloaded finger model is better controllable with (P, E, I) than with (S, E, I). Therefore, it can be conjectured that in the real finger the deep flexor rather than the superficial flexor will effectively control unloaded movement. Clinically this is confirmed by the fact that the superficial flexor can be removed, as is regularly done in tendon transposition surgery, without causing immediate lack of control in the unloaded finger, indicating that no substantial difference exists in basic motor use with or without S. Even when the moment arms of the flexor S would change to the extent that $A(S, E) \leqslant 0$ in expression (10) so that finger with the motor triplet (S, E, I) becomes uncontrollable, the deep flexor would ensure normal control [case of equation (12c)]. This situation changes when the PIP hyperextends and the terminal slips at the PIP bowstring ($r_{M2} < r_{T2}$) to the degree that one of conditions (11) is violated, so that the finger is uncontrollable by (E, I, P). A swanneck may then in principle be avoided by inactivating P and using S (Landsmeer, 1958). However, such finger control may be difficult to learn. When P dominates finger control in the PIP flexion range, it may also tend to dominate with hyperextended PIP, thus provoking a swanneck even when $A(S, E) > 0$.

The driving force of the claw hand deformity

When the interossei are paralysed, the unloaded finger with slack joint ligaments is unbalanced. By the tonus forces of the intact motors (extensor and flexors) the finger will then collapse into a 'clawing' end position, i.e. a position with a hyperextended MCP and a flexed PIP and DIP, in which minimally one of the joints is in its end position (normally the MCP). The unloaded finger then is in equilibrium, with the absent interosseus function substituted by the forces in the passively stretched joint ligaments and soft tissues at the MCP (Landsmeer, 1995; Spoor and Landsmeer, 1976). With flexed PIP, the interosseus force required to balance the deep flexor force is much greater than with an equal superficial flexor force (Fig. 3). Therefore, if in the real hand with intrinsic paralysis the tonus forces of P and S are equal, the strain in the soft tissues at the clawing end position caused by the deep flexor will be far greater than the strain caused by the superficial flexor (note that with the flexor S the clawing does not involve the DIP). Moreover, the greater the clawing (i.e. MCP hyperextension and PIP flexion), the greater the strain caused by the deep flexor will be, as it is proportional to the required interosseus force, which increases with the ratio r^*_{P2}/r_{P1}, which in its turn increases with clawing (r_{P1} is minimized with MCP hyperextension, while r^*_{P2} increases with PIP flexion (Fig. 3)). It follows that clawing is a positive feedback mechanism, which may help to explain the increase in the degree of clawing of the finger with time.

The finger of the musician with impaired PIP–DIP coupling mechanism

From the above it follows that the good controllability of the finger by the (P, E, I) motor triplet is the result of two delicate anatomic constructs: the PIP–DIP coupling mechanism, and the chiasma tendinum. This implies that disturbances in the proper functioning of these constructs, e.g. increased relative friction of the flexor tendons in the chiasma tendinum, or a decreased mobility of the terminal slips at the PIP joint, will affect the 'quality' of finger control, even if they do not reverse the conditions of control of expression (8). In the musician's hand even a slight decrease in the 'feeling' of control may be a handicap. Such complications may occur after e.g. fractions of the proximal phalanx or crush injuries which result in slight adhesions between the flexor tendons or between the fibres of the extensor assembly. Therefore, when after such injuries, even when healed with no apparent gross dysfunction, the 'feeling' of finger control is decreased, attention should also be given to the full rehabilitation of the mobility of the terminal slips of the extensor aponeurosis at the PIP, and the relative mobility of the flexor tendons.

CONCLUSIONS

In the present paper the controllability of the unloaded finger by either the deep flexor, extensor, interosseus, or by the superficial flexor, extensor and interosseus is theoretically investigated. It is shown that the controllability of the finger is determined by the 'degree of antagonism' (a concept defined in the text) of the flexors and extensor. For the deep flexor and the extensor this antagonism is a function of the PIP position. The following is concluded:

(i) The three-tendon (S, E, I) bi-articular chain is not well controllable, as S and E are too antagonistic.

(ii) For all PIP positions with the PIP not too (hyper) extended, the finger is better controllable by the (P, E, I) motor triplet than by the (S, E, I) motor triplet.

(iii) The controllability of the finger by the (P, E, I) motor triplet improves with PIP flexion.

(iv) In the finger with hyperextended PIP, the controllability with the motor triplet (P, E, I) may become worse than with (S, E, I) motor triplet, or even impossible.

It is shown that the chiasma tendinum and the dissociation of the extensor aponeurosis into a medial and terminal slips which insert in the middle and terminal phalanx, respectively, fundamentally improve the controllability of the finger by the (P, E, I) motor triplet with respect to the (S, E, I) motor triplet. Clinically, it is indicated that the claw-hand as resulting from interosseus paralysis is primordially caused by the (tonus) forces of extensor and the deep flexor, and not the superficial flexor; and further that small traumata affecting the smooth functioning of the mechanism which couples the PIP and DIP rotations may fundamentally decrease the controllability of the unloaded finger, e.g. in fast finger movements of the musician.

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