Ergonomics
Vol. 51, No. 2, February 2008, 156–167

Taylor & Francis
Taylor & Francis Group

Technical note

A new method for estimating hand internal loads from external force measurements

C. B. IRWIN and R. G. RADWIN*

Department of Biomedical Engineering, University of Wisconsin,
1550 Engineering Drive, Madison, WI 53706, USA

This study examines using force vectors measured using a directional strain gauge grip dynamometer for estimating finger flexor tendon tension. Fifty-three right-handed participants (25 males and 28 females) grasped varying-sized instrumented cylinders (2.54, 3.81, 5.08, 6.35 and 7.62 cm diameter) using a maximal voluntary power grip. The grip force vector magnitude and direction, referenced to the third metacarpal, was resolved by taking two orthogonal grip force measurements. A simple biomechanical model incorporating the flexor tendons was used to estimate long finger tendon tension during power grip. The flexor digitorum superficialis and the flexor digitorum profundus were assumed to create a moment about the metacarpal phalange (MCP) joint that equals and counteracts a moment around the MCP joint measured externally by the dynamometer. The model revealed that tendon tension increased by 130% from the smallest size handle to the largest, even though grip force magnitude decreased 36% for the same handles. The study demonstrates that grip force vectors may be useful for estimating internal hand forces.

Keywords: Upper extremity biomechanical model; Hand force; Grip force

1. Introduction

Biomechanical modelling of the hand is important for understanding how exerted forces act on the internal tissues for various hand functions, gripping tasks and handle designs. Quantitative mechanical hand modelling has been considered since the early 1960s (Landsmeer 1962) and has increased in complexity since (An *et al*. 1979, 1985, Spoor 1983, Valero-Cuevas *et al*. 1998, Fowler and Nicol 2000). Some models are quite

*Corresponding author. Email: radwin@bme.wisc.edu

Ergonomics
ISSN 0014-0139 print/ISSN 1366-5847 online © 2008 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130701526408

extensive and include all known intrinsic and extrinsic muscles involved in grasp (Chao *et al*. 1976, An *et al*. 1979, Spoor 1983, Valero-Cuevas *et al*. 1998, Li *et al*. 2001, Sancho-Bru *et al*. 2001). Although anatomically precise, these models are challenging to implement in practice, since they require input parameters that are often difficult or impossible to measure. Assumptions regarding muscle recruitment and optimization methods sometimes produce results that have been found inaccurate (Dennerlein *et al*. 1998).

Edgren *et al*. (2004) showed that maximal voluntary grip force can be measured using a strain gauge dynamometer by considering grip force as a vector composed of magnitude and direction. The study found that varying handle size affected grip force vector magnitude as well as direction. The objective of the current study was to explore if that method can be used for implementing a hand biomechanical model. A simple flexor tendon model, including the flexor digitorum superficialis (FDS) and the flexor digitorum profundus (FDP), was used for testing how grip force vectors can be used to observe how the flexor tendon tension changes for varying handle size.

2. Methods

Grip force was measured for 53 right-handed participants recruited from a manufacturing facility in the Midwest United States. All were healthy volunteers who gave informed consent to participate. Their ages ranged from 20 to 59 years. There were 25 males and 28 females. Hand length ranged from 15.9 cm to 21.0 cm, with a mean of 18.30 (SD 1.29) cm and hand breadth ranged from 7.9 to 11.7, with a mean of 10.1 (SD 0.93) cm for the right hand. The protocol for this experiment was reviewed and approved by the University of Wisconsin Human Subjects Committee. These are the same subjects used in Edgren *et al*. (2004).

A cylindrical strain gage dynamometer was used to measure force in a single axis of sensitivity and linearly summated forces applied along the handle length. The dynamometer is described in detail in Radwin *et al*. (1991). Different diameter aluminium caps were attached to the dynamometer providing cylindrical handles of 2.54, 3.81, 5.08, 6.35 and 7.62 cm diameter.

Participants were instructed to sit with the shoulder adducted and neutrally rotated, the elbow flexed at 90°, with the forearm and wrist in neutral position. The participants then grasped a cylindrical handle for 5 s at maximal voluntary contraction. The cylindrical handle was then rotated 90° and the procedure repeated with the same handle, in order to obtain orthogonal vectors that could be resolved into a single comprehensive grip force vector. This procedure was completed for each of the five handle sizes.

The long fingers were modelled as a mechanical system of four rigid links attached by hinge joints that allow a single degree of freedom. The three hinge joints were assumed frictionless. Buchholz and Armstrong (1991) studied the relationship between overall hand length and breadth related to finger phalanx length, breadth and depth and developed a set of empirical equations that modelled the finger segments as a system of ellipsoids. To determine the semi-axis dimensions of any particular finger segment, the overall hand dimension is multiplied by a predetermined coefficient such that:

$$SL = A_{ij} \times HL$$

where SL = segment length, A_{ij} = given coefficients for segment length model and HL = overall hand length.

The ellipsoids were offset such that 60% of the depth of the ellipsoid was below the segment long axis. Thus, the ellipsoids were not hinged directly on the centreline but were hinged slightly above. Soft tissue deformation was not modelled, due to the desire for simplicity and the fundamental complexity of modelling viscoelastic solids. Common abbreviations found in this paper and other hand-related literature are defined in table 1.

The Buchholz and Armstrong (1991) equations were used to determine the segment dimensions for each participant. The resulting finger segments were geometrically oriented to the handle with regard to a given reference point using AutoCAD 2004 software (Autodesk Inc., San Rafael, CA, USA). The metacarpal phalange (MCP) joint was aligned perpendicular to the axis of sensitivity of the dynamometer. In proximal-to-distal step-wise order, the ovaloid segments were rotated until they made contact with the handle surface (figure 1).

After each segment was in contact with the handle, joint angles were determined (figure 2). By superimposing the measured resultant force vector onto the overhead view of the finger-handle system, the point where the vector interacts with the hand was located (figure 3).

The two extrinsically-originating flexor tendons, the FDS and the FDP were the only two tendons included in the simple model. The basic premise of the model is that the overall moment about the MCP joint caused by the external load on the hand, dictated by gripping the dynamometer, is balanced by the moments about the MCP caused by the two flexor tendons. Balancing these moments ensures static equilibrium (figure 4).

The equations used in the model are listed below and divided into internal and external tendon moments. Variables are defined in table 2. Internal moments are created about the MCP joint by the FDP and FDS, while moments created by the resultant force vector (measured by the dynamometer) around the MCP joint are referred to as external moments.

Table 1. Abbreviations.

	Abbreviation	Meaning
Segments	PP	Proximal phalanx
	MP	Middle phalanx
	DP	Distal phalanx
Joints	MCP	Metacarpophalangeal
	PIP	Proximal interphalangeal
	DIP	Distal interphalangeal
Flexors	FDP	Flexor digitorum profundus
	FDS	Flexor digitorum superficialis
Extensors and Intrinsics	RI	Radial interosseus
	UI	Ulnar interosseus
	LUM	Lumbrical
	UB	Ulnar band
	RB	Radial band
	ES	Extensor slip
	EDC	Extensor digitorum communis
	TE	Terminal extensor

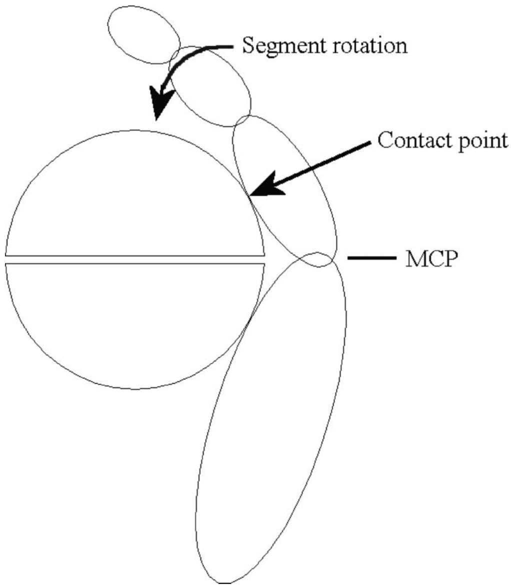

Figure 1. Ovaloid segment rotation. MCP = metacarpal phalange.

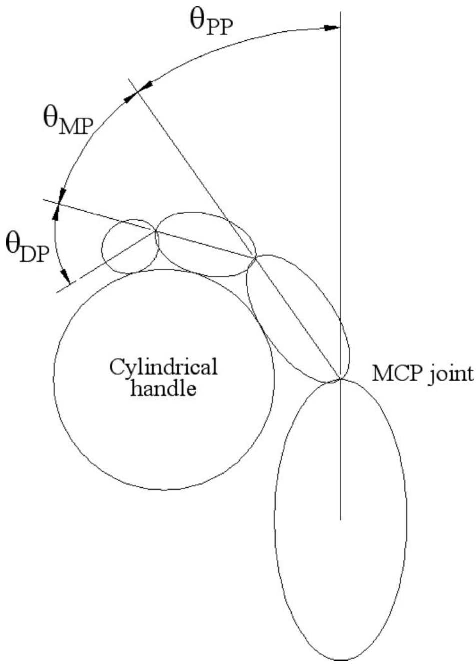

Figure 2. Finger segment angle definitions. PP = proximal; MP = middle; DP = distal; MCP = metacarpal phalange.

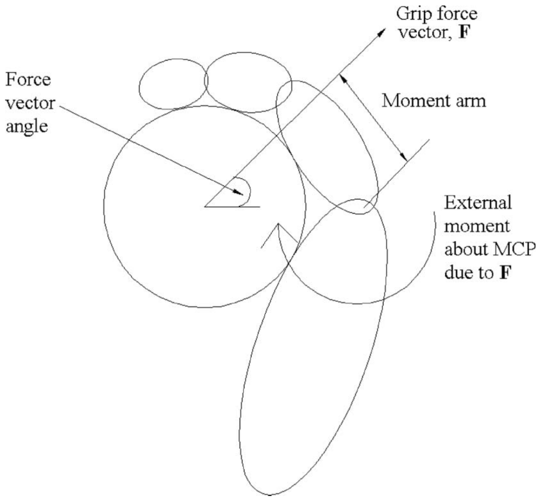

Figure 3. Superimposing force vector magnitude and angle data (from dynamometer) onto the geometric model. MCP = metacarpal phalange.

Internal tendon moments:

$$
\begin{aligned}
M_{\mathrm{Prox},FDP} &= (Cos\theta_{PP} + Sin\theta_{PP})L_{Moment,\mathrm{Prox},FDP}F_{FDP}\\
M_{\mathrm{Prox},FDS} &= (Cos\theta_{PP} + Sin\theta_{PP})L_{Moment,\mathrm{Prox},FDS}F_{FDS}\\
M_{\mathrm{Mid},FDP} &= (Cos\theta_{PP} + Sin\theta_{PP})L_{Phalanx,\mathrm{Prox}}[Cos(\theta_{PP} + \theta_{MP} - 90)\\
&\quad + (Sin(\theta_{PP} + \theta_{MP} - 90)]L_{Moment\mathrm{Mid},FDP}F_{FDP}\\
M_{\mathrm{Mid},FDS} &= (Cos\theta_{PP} + Sin\theta_{PP})L_{Phalanx,\mathrm{Prox}}[Cos(\theta_{PP} + \theta_{MP} - 90)\\
&\quad + (Sin(\theta_{PP} + \theta_{MP} - 90)]L_{Moment\mathrm{Mid},FDS}F_{FDS}\\
M_{\mathrm{Dist},FDP} &= (Cos\theta_{PP} + Sin\theta_{PP})L_{Phalanx,\mathrm{Prox}}[Cos(\theta_{PP} + \theta_{MP}) + Sin(\theta_{PP} + \theta_{MP})]L_{Phalanx,\mathrm{Mid}}\\
&\quad \times [Cos(\theta_{PP} + \theta_{MP} + \theta_{DP} - 90)\\
&\quad + Sin(\theta_{PP} + \theta_{MP} + \theta_{DP} - 90)]L_{Moment\mathrm{Dist},FDP}F_{FDP}
\end{aligned}
$$

External force moment on proximal phalanx:

$$M_{\mathrm{Prox,Force}} = (Cos\theta_{PP} + Sin\theta_{PP})L_{\mathrm{Prox,Force}}[Sin(90 - \theta_{PP}) + Cos(90 - \theta_{PP})]F_{\mathrm{Prox}}$$

External force moment on middle phalanx:

$$
\begin{aligned}
M_{\mathrm{Mid},X-dir,\mathrm{Force}} &= \left[L_{\mathrm{Mid,Force}}Cos(\theta_{PP} + \theta_{MP}) + L_{Phalanx,\mathrm{Prox}}Cos\theta_{PP}\right]\\
&\quad Sin(\theta_{PP} + \theta_{MP} - 90)F_{\mathrm{Mid}}\\
M_{\mathrm{Mid},Y-dir,\mathrm{Force}} &= -\left|L_{\mathrm{Mid,Force}}Sin(\theta_{PP} + \theta_{MP}) + L_{Phalanx,\mathrm{Prox}}Sin\theta_{PP}\right|\\
&\quad Cos(\theta_{PP} + \theta_{MP} - 90)F_{\mathrm{Mid}}
\end{aligned}
$$

Balancing internal tendon moments and external force moments:

$$
\begin{aligned}
&M_{\mathrm{Prox},FDP} + M_{\mathrm{Prox},FDS} + \left|M_{\mathrm{Mid},FDP}\right| + \left|M_{\mathrm{Mid},FDS}\right| + \left|M_{\mathrm{Dist},FDP}\right| = \left|M_{\mathrm{Prox,Force}}\right|\\
&\quad + \left|M_{\mathrm{Mid},X-dir,\mathrm{Force}} + M_{\mathrm{Mid},Y-dir,\mathrm{Force}}\right|
\end{aligned}
$$

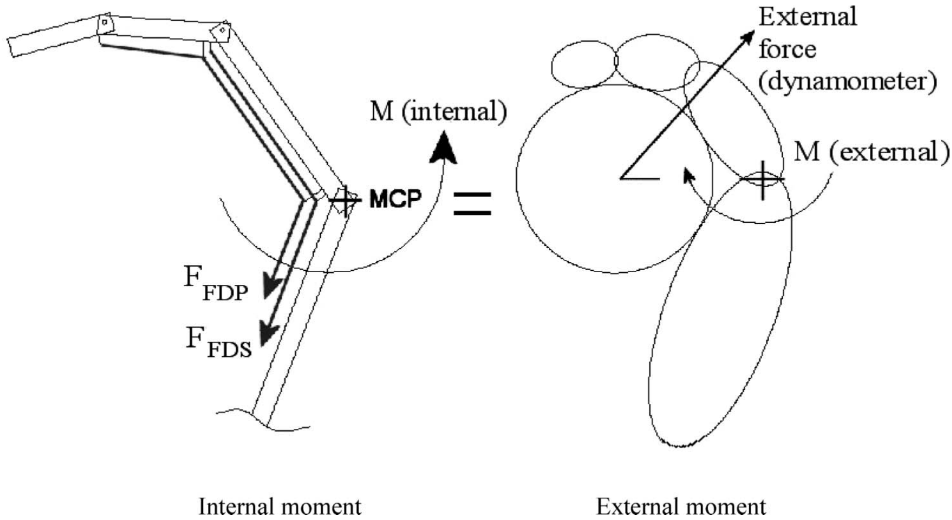

Figure 4. Internal vs. external moments in the long finger. MCP = metacarpal phalange; FDP = flexor digitorum profundus; FDS = flexor digitorum superficialis.

Table 2. Variables in the model.

Variable	Definition
$M_{\mathrm{Prox},FDP}$	Moment caused by FDP tendon acting on the proximal phalanx
$M_{\mathrm{Prox},FDS}$	Moment caused by FDS tendon acting on the proximal phalanx
$M_{\mathrm{Mid},FDP}$	Moment caused by FDP tendon acting on the middle phalanx
$M_{\mathrm{Mid},FDS}$	Moment caused by FDS tendon acting on the middle phalanx
$M_{\mathrm{Dist},FDP}$	Moment caused by FDP tendon acting on the distal phalanx
θ_{PP}	Finger joint angle between metacarpal and proximal phalanx (see figure 3)
θ_{MP}	Finger joint angle between proximal phalanx and middle phalanx (see figure 3)
θ_{DP}	Finger joint angle between middle phalanx and distal phalanx (see figure 3)
F_{FDP}	Tension in the FDP tendon
F_{FDS}	Tension in the FDS tendon
$L_{Phalanx,\mathrm{Prox}}$	Length of the proximal phalanx
$L_{Phalanx,\mathrm{Mid}}$	Length of the middle phalanx
$L_{Moment\mathrm{Prox},FDP}$	Length of the FDP moment arm on the proximal phalanx
$L_{Moment\mathrm{Prox},FDS}$	Length of the FDS moment arm on the proximal phalanx
$L_{Moment\mathrm{Mid},FDP}$	Length of the FDP moment arm on the middle phalanx
$L_{Moment\mathrm{Mid},FDS}$	Length of the FDS moment arm on the middle phalanx
$L_{Moment\mathrm{Dist},FDP}$	Length of the FDP moment arm on the distal phalanx
$M_{\mathrm{Prox,Force}}$	Moment caused by the externally measured force contacting the proximal phalanx
$M_{\mathrm{Mid},x-dir,\mathrm{Force}}$	Moment in the X-direction caused by the externally measured force contacting the middle phalanx
$M_{\mathrm{Mid},y-dir,\mathrm{Force}}$	Moment in the Y-direction caused by the externally measured force contacting the middle phalanx
$L_{\mathrm{Prox,Force}}$	Distance (from MCP joint) that the externally measured force acts along the long axis of the proximal phalanx
$L_{\mathrm{Mid,Force}}$	Distance (from PIP joint) that the externally force acts along the long axis of the middle phalange
F_{Prox}	Measured force from dynamometer on proximal phalanx
F_{Mid}	Measured force from dynamometer on middle phalanx

FDP = flexor digitorum profundus; FDS = flexor digitorum superficialis; MCP = metacarpal phalange; PIP = proximal interphalangeal.

In addition to using the dynamometer's physical dimensions to estimate joint angles, the grip force vector magnitude and direction data obtained from the dynamometer were used in the model as follows:

1. The grip force vector magnitude was used to calculate the 'external' moment about the MCP joint (see figure 3). In the case where this force vector intersects the finger on the middle phalanx, it was represented by F_{Mid} in the above equations.
2. The grip force vector direction was also used to calculate the 'external' moment. The measured direction describes where the force intersects the finger and therefore dictated the lengths of the moment arms, whose origin is about the MCP. In the case where the grip force vector intersects the middle phalanx, this information entered the above equations in the expression $L_{Mid,Force}$.

3. Results

The measured anthropometric data and the phalanx dimensions calculated from Buchholz and Armstrong (1991) are described in table 3.

Using the phalanx dimensions and handle geometry, finger joint angles could be estimated. The minimum, maximum and mean values for each joint angle are summarized in table 4.

Table 3. Anthropometric data.

	Overall measured				Calculations based on Buchholz (1991)					
					Index finger phalanx length (cm)			Index finger phalanx depth (cm)		
	Hand length (cm)	% ile	Hand breadth (cm)	% ile	Proximal (PP)	Middle (MP)	Distal (DP)	Proximal (PP)	Middle (MP)	Distal (DP)
Minimum	15.88	2.4	7.94	9.9	4.28	2.97	1.69	1.68	1.46	1.24
Mean	18.3	40.8	10.1	84.1	4.93	3.42	1.95	2.14	1.89	1.58
(SD)	(0.51)		(0.37)							
Maximum	20.96	96.2	11.75	100	5.65	3.92	2.24	2.49	2.16	1.83

Table 4. Finger segment angle data.

	Handle diameter (cm)								
	2.54			3.81			5.08		
	θpp	θmp	θdp	θpp	θmp	θdp	θpp	θmp	θdp
Minimum	40	80	15	37	61	21	34	47	21
Mean (SD)	43 (1.1)	95 (6.5)	37 (7.4)	40 (0.9)	75 (6.6)	40 (6.0)	37 (1.2)	60 (6.8)	42 (6.5)
Maximum	45	116	51	42	98	56	39	83	58
	6.35			7.62					
	θpp	θmp	θdp	θpp	θmp	θdp			
Minimum	32	36	26	30	26	27			
Mean (SD)	35 (1.2)	48 (6.6)	43 (6.6)	33 (1.2)	38 (6.2)	45 (5.7)			
Maximum	37	69	59	36	58	60			

pp = proximal; mp = middle; dp = distal.

A summary of maximal grip force vs. handle diameter (Edgren *et al*. 2004) in addition to the estimated FDP tendon tension (normalized by the tension value of least magnitude for the smallest handle) is displayed in figure 5.

Flexor tendon tension for each discrete exertion was then normalized by the grip force magnitude for that exertion. The results were then broken down into the lower, middle and upper one-third percentiles of hand size based on Greiner (1991). These data are plotted in figure 6. The effects of both the handle ($F(4,200) = 98.7$, $p < 0.001$) and the

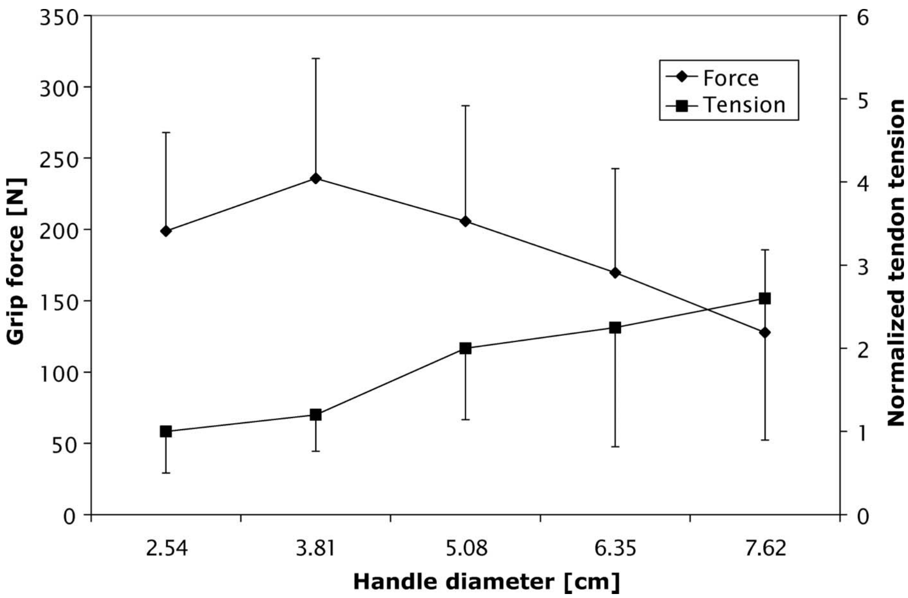

Figure 5. Tendon tension normalized by least value and overall grip force vs. handle diameter.

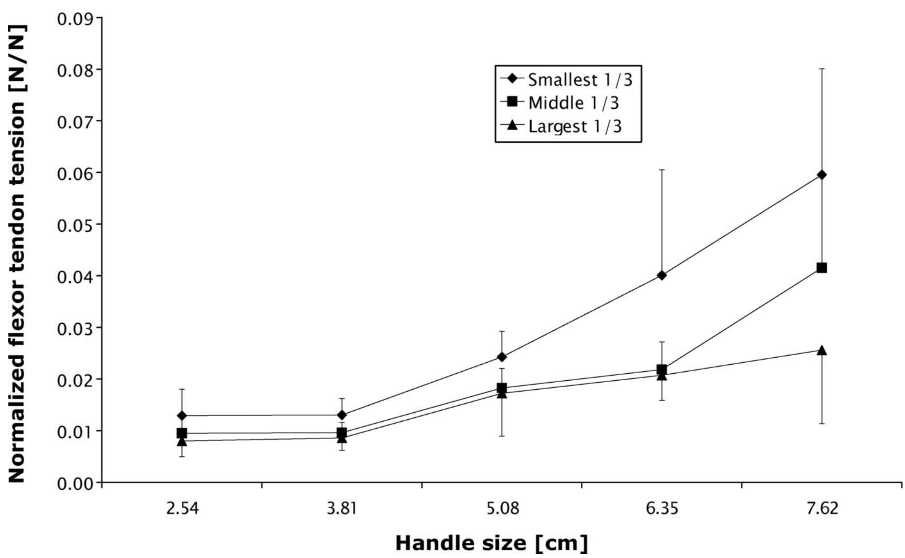

Figure 6. Tendon tension normalized by total grip force magnitude vs. handle size.

interaction of the handle and hand size ($F(4,200) = 9.2$, $p < 0.001$) were statistically significant.

4. Discussion

Valero-Cuevas (2005) argued that biomechanical models should not increase in complexity beyond what is necessary to explain the data. Previous researchers have constructed biomechanical hand models that include most, if not all, of the relevant structures of the finger (Chao *et al.* 1976, An *et al.* 1979, Spoor 1983, Valero-Cuevas *et al.* 1998, Li *et al.* 2001, Sancho-Bru *et al.* 2001). Despite these advances in modelling, inaccuracies and measurement difficulties still remain. Whether due to structural inconsistencies between the actual finger and the model or simply parameter values, most models to date have been limited in their ability to accurately predict measured data (Dennerlein *et al.* 1998). The modelling in the current study was not intended to deliver accurate tendon tension predictions per se, but rather to demonstrate that limited external grip force vector measurements may be useful for driving a simple but pragmatic finger biomechanical model. The successful application of these measurements allows the conclusion that measurements that resolve complex arrays of forces in the hands may provide a practical means for internal force predictions without the need for measuring every force component.

Li *et al.* (2001) examined finger tendon forces using two models, one that included the extensor mechanism and one that did not. Their findings suggest that the extensor mechanism is important for forces directed into the finger proximal to the proximal interphalangeal (PIP) joint because the extensors transmit force from the lumbricals to the interphalangeal joints. The overall grip force vectors measured in the current study by the grip force dynamometer were often directed into the finger proximal to the PIP joint (figure 3). Citing the results from Li *et al.* (2001), this suggests that the lumbricals, and thus the extensor mechanism, should be included in the author's simple model. It should, however, be noted that the grip force vector from the grip dynamometer is a summation of the forces produced by the whole of the finger and hand, and not just a point force application. If the force is thought of in this manner, namely, spread across the finger segments as suggested by Amis (1987), the proximal finger link only contributes a percentage to the overall force vector and it can be argued that if the lumbricals, and thus the extensors, are left out of the model for simplicity, the model can still adequately explain the data.

It is acknowledged that the predicted long tendon tensions presented in this paper are relative, rather than absolute, and influenced proportionally by the handle geometry. The approach however demonstrates that estimates of internal forces using limited external force vector measurements are feasible. The exact role of both the long extensor tendons and the lumbricals in grip is still under review. Previous researchers have used electromyography to simultaneously record signals from any combination of the seven long finger muscles that can be activated during finger force production. In order to obtain more accurate measurements, fine-wire electrodes might be used to eliminate the possibility of picking up electrical cross-talk from different muscles that make surface electrodes unreliable. Even when using indwelling electrodes, it can be difficult to get accurate electrode placement and, in some situations, proper placement requires considering anatomical variations and anomalies (Burgar *et al.* 1997). The difficulties of placing electrodes in the forearm make validation of calculated tendon tensions very difficult.

The angles θ_{PP}, θ_{MP}, and θ_{DP} were all estimated from the measured hand length in conjunction with Buchholz and Armstrong (1991) and the protocol described above. Segment lengths, for instance, $L_{Phalanx,\mathrm{Prox}}$, also come from the ovaloid method of estimating segment dimensions from overall hand length and breadth. Since no two participants had exactly the same overall hand length and breadth, no two participants had exactly the same combination of segment lengths and joint angles. Even if two participants produced exactly the same grip force vector, variations in joint angles and segment lengths alter the moment arms for calculating moments around the MCP joint and therefore alter the force burdens on the tendons (see figures 2 and 3).

The simplified tendon model in the current study does not account for the thumb. The long finger extensor mechanism, the intrinsic muscles and any passive joint moments caused by friction, etc. are also omitted. If these omissions were included into the model they would almost certainly act to increase the tensions in both the FDS and the FDP. Therefore, the tensions calculated by the simplified model are conservative and the actual magnitude of the tension in these tendons is undoubtedly greater. That said, it was assumed that the trends observed while omitting these effects and structures would be similar to the trends of a more anatomically and physiologically accurate model.

The current data, like previous studies (Harkonen *et al.* 1993, Sancho-Bru *et al.* 2003), demonstrate that there is an 'optimal' handle diameter to produce the highest magnitude grip force. Research by Amis (1987) and Kong and Lowe (2005) both measured grip force on cylindrical handles by first measuring the grip force produced by each individual finger link and then simply summing all the link forces together. Both studies found that participants were able to produce the greatest 'summed' grip force while gripping the smallest cylindrical handle for each respective study. Combining this information with the present results, in which the smallest handle was not the 'optimal' sized handle by force production standards suggest that, even though the fingers and hand are producing the greatest magnitude of 'summed' force on the smallest handle, not all of this force is actually productive in squeezing the handle. It is possible that some of this 'summed' force is lost in shear or is directed in a non-normal direction with regard to the cylindrical handle. Using a linearly summing hand dynamometer to measure grip force on a handle may provide a more useful description of hand–handle grip dynamics since the linearly summing dynamometer provides a picture of the useful forces that the handle actually incurs regardless of what forces the hand and fingers are producing. The dynamometer is suitable for attaching to tools and equipment for evaluations of internal grip forces.

The current study demonstrates that even though mean grip force magnitude decreases from 236 N to 128 N (a 46% decrease) from the 'optimal' sized handle (3.81 cm) to the largest handle (7.61 cm), flexor tendon tension increases 117% between the two handle sizes. This suggests that the muscles and tendons of the hand and arm can be working considerably more than one would conclude if only the grip force magnitude values were examined.

Although a powerful tool, the current grip dynamometer has several limitations, some previously discussed. Thumb forces are not isolated and two force measurements must be taken by orienting the dynamometer in different directions. Better tendon tension estimates might be achieved using better external force measurements. A new dynamometer is being developed in the author's laboratory that addresses many of the limitations of the current dynamometer. In addition to isolating the forces produced by the thumb, the new dynamometer will be able to measure two discrete grip force vectors acting on the fingers in one exertion. Measuring two vectors instead of one along the fingers may provide more accurate tendon tension predictions. Eliminating the need for the dynamometer to be rotated orthogonally between measurements offers the possibility of using handles with non-uniform cross sections and arbitrary shapes. This may lead to better ergonomic handles.

5. Conclusions

A biomechanical model in conjunction with grip force vector measurements is feasible and can yield a better understanding of stresses in the hand and arm during grip. This biomechanical information can sometimes lead to conclusions that are different than just using grip force measurements alone. For example, gripping a large diameter (7.62 cm) cylindrical handle resulted in 108 N less grip force strength than for a small diameter handle (2.54 cm), while predicted tendon tension in the fingers for the large handle was more than twice than for the small handle.

Acknowledgements

The authors wish to thank Ms. Cally Edgren for her role in collecting the strength data used in this study.

References

Amis, A.A., 1987, Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters. *Journal of Biomedical Engineering*, **9,** 313–320.

An, K.N., Chao, E.Y., Cooney, W.P. and Linscheid, R.L., 1979, Normative model of human hand for biomechanical analysis. *Journal of Biomechanics*, **12,** 775–788.

An, K.N., Chao, E.Y., Cooney, W.P. and Linscheid, R.L., 1985, Forces in the normal and abnormal hand. *Journal of Orthopedic Research*, **3,** 202–211.

Buchholz, B. and Armstrong, T.J., 1991, An ellipsoidal representation of human hand anthropometry. *Human Factors*, **33,** 429–441.

Burgar, C.G., Valero-Cuevas, F.J. and Hentz, V.R., 1997, Fine-wire electromyographic recording during force generation – application to index finger kinesiologic studies. *American Journal of Physical Medicine & Rehabilitation*, **76,** 494–501.

Chao, E.Y., Opgrande, J.D. and Axmear, F.E., 1976, Three-dimensional force analysis of finger joints in selected isometric hand function. *Journal of Biomechanics*, **9,** 287–396.

Dennerlein, J.T., Diao, E., Mote, C.D. Jr. and Rempel, D.M., 1998, Tensions in the flexor digitorum superficialis are higher than a current model predicts. *Journal of Biomechanics*, **31,** 295–301.

Edgren, C., Radwin, R.G. and Irwin, C.I., 2004, Grip force vectors for varying handle diameters and hand sizes. *Human Factors*, **46,** 244–251.

Fowler, N.K. and Nicol, A.C., 2000, Interphalangeal joint and tendon forces: normal model and biomechanical consequences of surgical reconstruction. *Journal of Biomechanics*, **33,** 1055–1062.

Greiner, T.M., 1991, *Hand Anthropometry of U.S. Army Personnel,* U.S. Army Report NATICK/TR-92/011 (Natick, MA: US Army Natick, Research, Development and Engineering Center).

Harkonen, R., Piirtomaa, M. and Alaranto, H., 1993, Grip strength and hand position of the dynamometer in 204 Finnish adults. *Journal of Hand Surgery-British and European*, **18B,** 129–132.

Kong, Y.K. and Lowe, B.D., 2005, Optimal cylindrical handle diameter for grip force tasks. *International Journal of Industrial Ergonomics*, **35,** 495–507.

Landsmeer, J.M.F., 1962, Power grip and precision handling. *Annals of Rheumatoid Disease*, **21,** 164–169.

Li, Z.M., Zatsiorsky, V.M. and Latash, M.L., 2001, The effect of finger extensor mechanism on the flexor force during isometric tasks. *Journal of Biomechanics*, **34,** 1097–1102.

Radwin, R.G., Masters, G.P. and Lupton, F.W., 1991, A linear force-summing hand dynamometer independent of point of application. *Applied Ergonomics*, **22,** 339–345.

Sancho-Bru, J.L., Giurintano, D.J., Perez-Gonzalez, A. and Vergara, M., 2003, Optimum tool handle diameter for a cylinder grip. *Journal of Hand Therapy*, **16,** 337–342.

Sancho-Bru, J.L., Perez-Gonzalez, A., Vergara-Monedero, M. and Giurintano, D., 2001, A 3-D dynamic model of human finger fur studying free movements. *Journal of Biomechanics*, **34,** 1491–1500.

Spoor, C.W., 1983, Balancing a force on the fingertip of a two-dimensional finger model without intrinsic muscles. *Journal of Biomechanics*, **16,** 497–504.

Valero-Cuevas, F.J., 2005, An integrative approach to the biomechanical function and neuromuscular control of the fingers. *Journal of Biomechanics*, **38,** 673–684.

Valero-Cuevas, F.J., Zajac, F.E. and Burgar, C.G., 1998, Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. *Journal of Biomechanics*, **31,** 693–703.