A three-dimensional biomechanical analysis of the index finger, incorporating measured loading data for selected activities of daily living.

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Introduction

Biomechanical models of the finger joints can be limited in their ability to accurately predict tendon and joint loads by oversimplification of external loading patterns or by assumptions made to reduce indeterminacy of the analysis. Several previous studies of the finger have used planar analyses or have restricted the three-dimensional model by ignoring equilibrium requirements for ad-abduction or internal-external rotation at the proximal interphalangeal joint. To reduce model complexity, relaxation of extensor muscles during grip and pinch activities has been assumed and in some models, combination of intrinsic muscles has been suggested.

Few studies use measured three-dimensional external loading data in the analysis of tendon and joint loads. External loading systems applied to the finger during activities of daily living are complex (Fowler et al., 2001a) and their equilibrium by joint and muscle forces should be considered in a three-dimensional context. In this study, a comprehensive index finger model has been developed, incorporating three-dimensional analysis of the metacarpophalangeal and proximal interphalangeal joints and using measured loading data for selected activities of daily living.

Methods

External loads applied to the index finger were measured using a sensitive six-component force transducer coupled with six-camera motion analysis. Eight subjects performed eleven simulated tasks with varied power and precision grips. These activities included opening/closing jar/tap and using a lateral pinch grip to turn a key in a lock. High resolution MRI scans were used to provide 3-D tendon and joint geometrical data for the model (Fowler et al., 2001b). An optimisation routine was used to minimise maximal stress in 19 intrinsic and extrinsic elements. Collateral ligaments at the MCP and PIP joints were included and the model was further constrained by considering the interrelationships of structures forming the extensor mechanism.

Joint contact forces acting on the articulating surfaces of the proximal phalanx are resolved into three orthogonal components. Each component is constrained to pass through the MCP joint centre. The resultant force is further constrained to act within the limits of the concave edge of the proximal phalanx articulating surface. At the PIP joint, the proximal phalangeal head has a bi-condylar articulating surface and under certain loading conditions, it is possible for one condyle to be loaded preferentially. Two independent joint contact forces under the same constraints (radial and ulnar) have been used to simulate this effect (Fowler and Nicol, 2000).

A linear optimisation method was used to find the optimum solution to the indeterminate set of combined constraint and equilibrium equations. A cost function minimising overall maximum tendon stress, $\sigma$, was selected, with the additional inequality constraints that

$$\frac{T_i}{CSA_i} \leq \sigma, \quad i = 1 \text{ to } n$$
where \( n \) is the number of tendons and ligaments included in the optimisation and \( \text{CSA}_i \) and \( T_i \) are the cross section area and force generated in the \( i^{th} \) tendon or ligament respectively. This approach was developed and justified by An et al. (1984), in a biomechanical model of the elbow joint, and lead to predicted sets of muscle contraction forces that correlated well with experimentally measured levels of myoelectric activity.

**Results & discussion**

Figure 1 shows the predicted forces in each structure when the resultant MCP joint contact force is at its peak for each activity. The results are the average of 8 subjects completing each activity 3 times. Table 1 gives the external applied loads and calculated joint contact forces for the same series of activities.

![Bar chart showing predicted forces in the main model components for jar and tap opening/closing and for key turning activities.](image)

**Figure 1**: Mean predicted forces (N) in the main model components for jar and tap opening/closing and for key turning activities. \( \text{fdp} = \) flexor digitorum profundus, \( \text{fds} = \) flexor digitorum superficialis, \( \text{ect} = \) extensor communis, \( \text{eit} = \) extensor indicis, \( \text{lur} = \) lumbrical, \( \text{dir} = \) dorsal interosseous, \( \text{piu} = \) palmar interosseous.

<table>
<thead>
<tr>
<th>Activity</th>
<th><strong>External Loads</strong></th>
<th><strong>MCP joint forces</strong></th>
<th><strong>PIP joint forces</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( M_x )</td>
<td>( M_y )</td>
<td>( M_z )</td>
</tr>
<tr>
<td>Jar</td>
<td>0.2</td>
<td>-0.2</td>
<td>-1.0</td>
</tr>
<tr>
<td>Tap</td>
<td>-0.4</td>
<td>-0.8</td>
<td>-0.8</td>
</tr>
<tr>
<td>Key</td>
<td>1.2</td>
<td>0.2</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

Table 1: Maximum averaged external applied moments (Nm) and forces (N), with calculated joint contact forces for jar and tap opening/closing and for key turning activities. Positive directions for axis system: \( x \)-volarly, \( y \)-axial (proximally), \( z \)-radially/\( M_x \)-adduction, \( My \)-pronation, \( Mz \)-flexion.

Complex loading patterns exist at all three finger joints during activities of daily living, showing the importance of a fully 3-dimensional analysis. At the MCP joint mean applied adduction moments of up to 1.6Nm are balanced by the abduction moment generated by the first dorsal interosseous. According to Fowler et al. (2001b), at large angles of flexion the first dorsal interosseous is more efficient as a pronator and a flexor than as an abductor. Where large external applied adduction moments are combined with pronation or small supination moments, antagonism at the MCP joint is exhibited. Due to the bony geometry of the MCP joint, the joint contact forces cannot provide resistance to moments applied in any plane: in the current model joint contact forces are constrained to pass through the instantaneous joint centre. The collateral ligaments do have a role in resisting applied adduction/abduction or pronation/supination moments, particularly where use of the dorsal interosseous as a strong abductor also results in a large antagonistic pronation moment.
In the model less use is made of the other intrinsic muscles, the lumbral and palmar interosseous. Tendinous attachments to the extensor apparatus from these two muscles link the MCP and PIP joints such that flexion of the MCP joint generates an extension moment at the PIP joint. For all activities, the external applied moments in the sagittal plane tend to extend both joints and there is no requirement for extension of the PIP joint except for antagonistic purposes. The lumbral assists the dorsal interosseus in pronation of the MCP joint and at flexion angles of greater than 40º offers little resistance to moments in the coronal plane (Fowler et al., 2001b). Although its cross section area is only 15% of the dorsal interosseous muscle, the lumbral also contributes to MCP joint flexion (Lauer et al., 1999). The lumbral’s origin on the flexor profundus tendon allows it to transfer flexor profundus tension to provide extension at the PIP joint (Thomas et al., 1968). (In the current model fdp represents the flexor profundus tendon distal to the lumbral origin.) The palmar interosseous muscle is used to adduct, supinate and flex the MCP joint and is frequently used by the model as antagonist to dorsal interosseous.

Details of the internal force distribution required to balance these 3-dimensional external loads are highly relevant, both to the design of prostheses and the assessment of soft tissue surgical procedures.

References


Fowler NK, Nicol AC, Condon B, Hadley D (2001b) Method of determination of three dimensional index finger moment arms and tendon lines of action using high resolution MRI scans. J. Biomechanics, 34;6;791-797.


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