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A NOVEL BIOMECHANICAL MODEL TO EVALUATE THE LOADS IN HUMAN FINGER TENDON NETWORK

[1]Dan Hu, [1] Lei Ren and [2] David Howard
[1]School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M60 1QD, UK
email: lei.ren@manchester.ac.uk
[2]School of Computing, Science and Engineering, University of Salford, Salford, M5 4WT, UK

SUMMARY
This study presents a novel biomechanical model to evaluate the mechanical loading of human finger extensor tendons, which consists of a tendinous network wrapping over the phalange's dorsum. The tendons are modeled as interconnected linear springs, the stiffness of which depends on its current length. To evaluate the tendon forces in the network, the Principle of Minimum Total Potential Energy was applied. The calculated tendon displacements and forces appear to be in the reasonable range. An automatic wrapping algorithm was also developed to describe the contact interactions between tendons and bones during tendon network moving. Future work involves the integration of the automatic wrapping algorithm into the energy based biomechanical framework.

INTRODUCTION
Studies on human fingers biomechanics can help improve our understanding of the interplay between the complex hand structure and its various biomechanical functions. This may have broad applications in clinical diagnosis of hand diseases, hand surgical treatment and planning and also biomimetic hand design and development etc. The current challenge in hand biomechanical modeling study is how to describe the mechanical behavior of the complex finger extensor mechanism, which is formed by continuous network wrapping over the phalanges. Normally it is constructed by solving the equilibrium equations of each finger joint, which brings the problem of indeterminacy [1]. Typical remedy to this problem is to eliminate those redundant and unknown tendon forces based on assumptions or to minimize a cost function assumed to be the performance objective of the system [2]. Recently, a relaxation method based on geometry to predict the tendon tensions in 3D environment has been developed [3], but is very time-consuming computationally due to the numerous iterations involved in the algorithm. In this study, a novel methodology based on the geometrical property of the network has been proposed by integrating an automatic tendon wrapping method into a minimizing energy principle.

METHODS
The whole biomechanical system is represented by a tendon network consisting of many interconnected tendon components. Each individual tendon component is modeled as a spring element with stiffness defined as:

$$k(l)=\begin{cases}K & if \quad l \ge l_0 \\ 0 & if \quad l < l_0\end{cases} \tag{1}$$

Here K is the stiffness of individual tendon element, l denotes the tendon length, and l_0 is the slack tendon length. The tendon force can be calculated as $F = k(l)\cdot\Delta l$. Then the Principle of Minimum Total Potential Energy is applied to the network to derive loads at each individual tendon element

$$\delta\prod = \delta(U+V) = 0 \tag{2}$$

where $\prod$ is the total system potential energy, U is the strain energy stored in the system and V is the potential energy of the external forces. According to the principle, if the external forces are applied to the tendon network, the positions of the network nodes will change until the system reached a new equilibrium state. Thereafter the tendon forces can be calculated based on the new position of the tendon network nodes $p=(p_x, p_y, p_z)$

$$\frac{\partial(\sum_{i=1}^{m} 1/2 k_i(l)\Delta l^2 - \sum_{j=1}^{n} F_j s_j)}{\partial p} = 0 \tag{3}$$

where the $F_j s_j$ represents the work of external force,

To represent the contact between the tendon network and the realistic bone geometry, an automatic wrapping algorithm has been developed. The bone surface is reconstructed based on triangle patches using scanning techniques (see Figure 1). P is the contact point on the line AB, τ is the tangential unit vector, n is the normal unit vector and r is the unit vector perpendicular to both τ and n. Since there is no friction between the bone and the tendon, the sum of component forces along the tangential direction of AB equals zero:

$$[T_{i-1}(t_{i-1},t_i) + T_{i+1}(t_{i+1},t_i)]\cdot\tau_i(t_i) = 0 \tag{6}$$

$$\tau_i(t_i) = \frac{dP_i/dt_i}{\|dP_i/dt_i\|} \tag{7}$$

$$T\frac{P_{i-1}(t_{i-1})-P_i(t_i)}{\left\|P_{i-1}(t_{i-1})-P_i(t_i)\right\|}\cdot\frac{dP_i/dt_i}{\left\|dP_i/dt_i\right\|} \quad (8)$$
$$+T\frac{P_{i+1}(t_{i+1})-P_i(t_i)}{\left\|P_{i+1}(t_{i+1})-P_i(t_i)\right\|}\cdot\frac{dP_i/dt_i}{\left\|dP_i/dt_i\right\|}=0$$

where $T_{i-1}(t_{i-1},t_i)$ and $T_{i+1}(t_{i+1},t_i)$ are the tension forces at point P applied by the tendon with equal magnitude of T. t is the ratio of point P between A and B, which strictly satisfies the condition of $0\le t\le 1$.

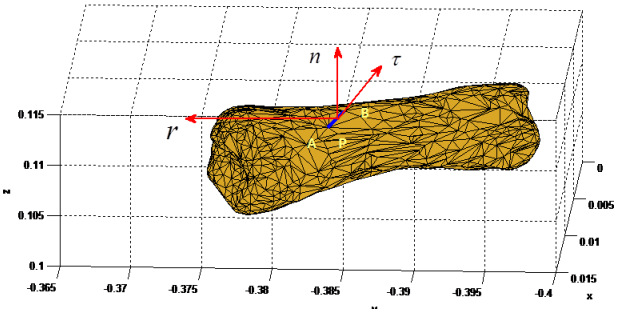

Figure 1: Contact interaction between tendon and bone

The algorithm starts to find the contact line segments automatically based on the initial possible path defined. In this method, the surface triangle patches sharing the same vertex form a polygon .The contact point is defined from one polygon to the adjacent polygon sharing the same side line. When adding one more line segment into the wrapping, the algorithm recalculate all the parameters t_i to ensure that all the lines are proper contact lines. For those lines on which the contact points sliding beyond the end points, they will be replaced by other line candidates, until the parameters for all the lines are in the right range.

RESULTS AND DISCUSSION

The simplified structure of the tendon network of the index finger is shown in Figure 2. The positions of the node points are determined based on anatomy literatures, and straight lines are used to connect the nodes. External finger tendon loads are applied along the directions defined by the blue lines based on literatures (5N for LU (Lumbrical), 2.5N for RI (Radial Interosseous), 5N for LE (Long Extensor) and 2.5N for UI (Ulnar Interosseous)) [5].

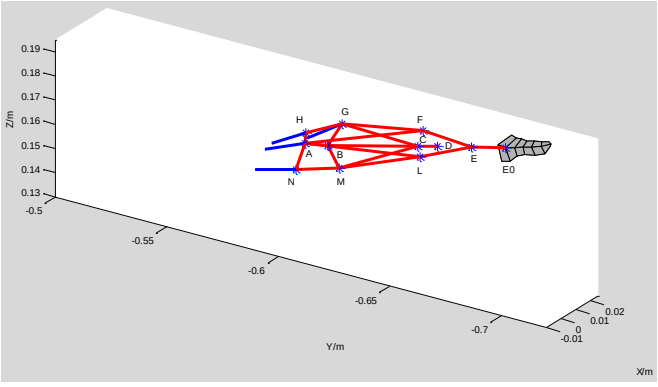

Figure 2: Simplified tendon network structure

By solving the partial differentiation equations of the total potential energy with respect to the nodes' positions of the tendon network (i.e. floating points of A, B, C, E, F, G, H, L, M, N, and D, E0 are insertion points of tendons), the forces on each tendon components are calculated (see Table 1). It can be seen that most of the tendons are taut except for segment HA, MB and NA. Due to the definition specified in Equation (1), the forces experienced by these three segments are 0. The maximum force of the tendon components is 10.6313N in CD, which is smaller than the total external forces of 15N.

In addition, the automatic wrapping algorithm has applied to index finger to represent the musculoskeletal geometry of the finger tendon network (see Figure 3). This will be integrated into the energy based force evaluation framework in the future.

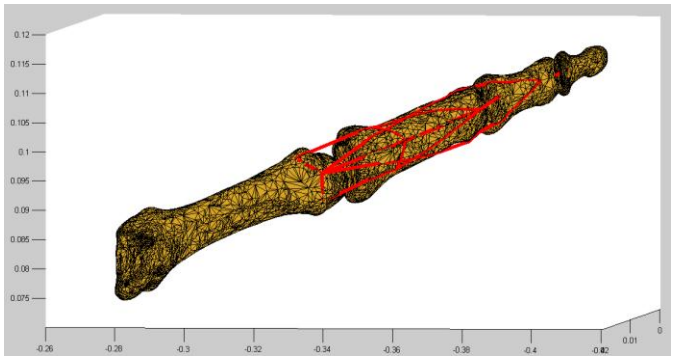

Figure 3: Index finger tendon network wrapping

Table 1: Force of each tendon network component

Component	Force (N)	Component	Force (N)
E0E	5.4518	EL	2.3473
AB	2.552	LM	0.4117
BC	2.709	MN	2.5
CD	10.6313	MB	0
EF	3.2076	NA	0
FG	2.230	FA	0.7108
GH	2.5	GC	5.2942
GB	0.6149	LA	1.6860
HA	0	MC	2.0064

CONCLUSIONS

A novel computational framework based on the Principle of Minimum Total Potential Energy is proposed to evaluate the mechanical responses of human finger tendon network. The tendons are modeled as linear springs only subjected to tensile loads, of which the stiffness values depend on the current tendon length. Based on the minimizing energy principle, the forces on each tendon components can be calculated analytically. Furthermore, an automatic wrapping algorithm has been developed to represent the surface contacts between the bones and tendon network.

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