Proceedings of the ASME 2009 Summer Bioengineering Conference (SBC2009)
June 17-21, Resort at Squaw Creek, Lake Tahoe, CA, USA

SBC2009-206889

A FAST SIMULATOR TO MODEL COMPLEX TENDON-BONE INTERACTIONS: APPLICATION TO THE TENDINOUS NETWORKS CONTROLLING THE FINGERS

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INTRODUCTION

Forces generated by the muscles actuating the fingers are transmitted through a complex network of tendons. Current models of the hand either ignore or simplify the structure of these networks [1]. It has been shown that the deformable nature of these tendinous networks results in a nonlinear transformation of muscle forces [2]. Our long-term objective is to understand how the topology of this network affects the control of finger force and motion. To achieve this, we will use a machine learning approach to evolve models of this network that can best replicate experimental results [3]. Here we present an anatomically realistic solver developed to model mechanical force transmission by a network of tendons in the human fingers. While most existing solvers neglect mechanics of tendon networks, there has been recent work on dynamic simulators accounting for tendon-bone interactions [4]. The solver we present here advances work in this field by being able to simulate mechanics of complex networks wrapped on arbitrarily shaped objects (like bones), and can be effectively used to model isometric force production in complex biomechanical systems. Its speed makes it an ideal simulation engine for the evolutionary algorithms we use to infer complex anatomical structures from sparse experimentation [3].

METHODS

Previously, a relaxation algorithm was used to simulate mechanics of tendon networks in 2D and for networks on simplified models of bones in 3D [3]. Here we use the finite element method to expand this work to develop a simulator of elastic networks interacting with arbitrarily shaped rigid objects. The solver assumes the solid surface to be frictionless, and the elastic network is free to deform and slide over the surface while the resulting contact forces can be determined.

A 3D polygonal surface model of scanned hand bones was obtained from the Stereolithography Archive at Clemson University. For now, the bones of the hand were modeled as a single rigid solid fixed to the global coordinate space. The tendon network was modeled as a network of elastic string elements connecting at nodes, where each element behaved like a truss element in tension but did not transmit force in compression. All tendon elements were assigned a constant elastic modulus of 1 GPa, a realistic value from the literature [5] and a cross sectional area of 0.25 mm^2. The inputs to the model were constant muscle forces at the input nodes and the calculated outputs were the displacements of all nodes, as well as the reaction forces generated at the points of attachment of tendon to bone.

The problem is nonlinear because tendons transmit force only in tension. Hence an incremental-iterative Newton-Raphson technique was used to solve the finite element problem [6]. First the initial configuration of the network was defined in the same 3D coordinate space as the rigid polygon model of the bones. A node-penetration test was performed to check if any node was penetrating the solid. This was done by checking the sign of the dot product of the vector from the node to the centroid of the closest triangle and the outward normal vector to that triangle. If a node was penetrating the solid, the node was pushed out to the surface by a restoration force created by a constraint spring element from the nearest point on the surface to the penetrating node. This spring element had a negligible resting length and high stiffness, and represented the force that a solid surface applies to prevent penetration. Then an element-penetration test was performed by repeating the node penetration test at distinct points on the element. If a point on the element was penetrating the solid, a new node was created at that point and pushed to the surface in the manner described above.

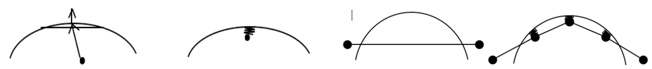

Fig. 1. Tests (a) Node-penetration; (b) Element-penetration

Once node- and element-penetration tests were performed, the tangent stiffness matrix and residue vector were calculated for every element. These were assembled and the displacements of the nodes were calculated for small increments in load using the iterative Newton-Raphson method. The node- and element-penetration tests were repeated for every load increment.

RESULTS

Figure 2 shows a sample tendon network draped over the bones of the hand.

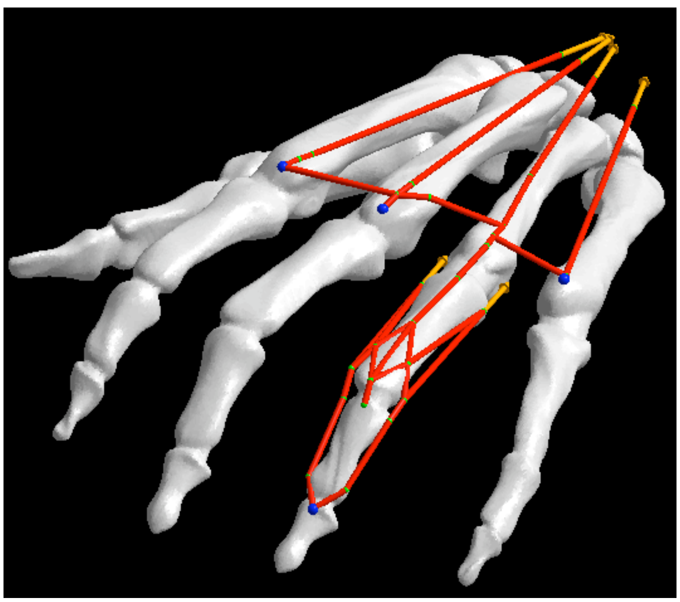

Figure 2: Winslow's tendinous network draped on the ring finger and the junctura tendinae draped on the hand

As an example of the use of this simulator, the nonlinearity in force transmission of these tendon networks can be seen in the example of Winslow's tendinous network (Figure 3) which transmits forces from the extensor digitorum communis (EDC) and the dorsal and palmar interosseous muscles to two points of attachment on the phalanges: the terminal slip (on the distal phalanx) and the proximal slip (on the middle phalanx) (Figure 3). Here, two of the input forces (generated by the interossei) were kept constant and one input force (generated by the EDC) was increased. The ratio of the forces generated at the terminal and proximal slips was calculated. The nonlinearity arises entirely due to the deformations in the tendon network. (The elastic modulus was assumed constant for this simulation).

DISCUSSION AND CONCLUSIONS

We have developed a quasi-static solver that can model complex elastic networks interacting with arbitrarily shaped objects like bones.

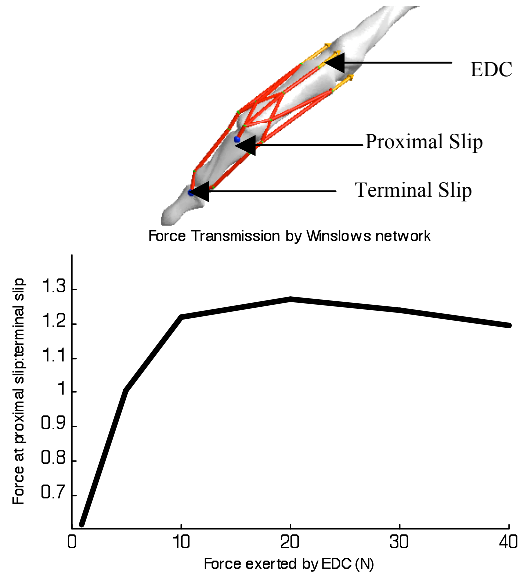

Figure 3: Winslow's network on finger [Label EDC and interossei, Makek line weight heavier]

The speed and robustness of this simulator allows us to now integrate this finite element solver with the evolutionary algorithms developed in [3] to evolve models of the tendon network of the hand that can best replicate real experimental data. Each candidate model of the tendon network will be simulated using the finite element solver described here.

ACKNOWLEDGEMENTS

We would like to thank Dr Anupam Saxena and Qian-Yi Zhou for their inputs. This material is based upon work supported by the National Science Foundation under Grants No. 0237258 (CAREER award) and No. 0312271 (ITR project); This publication was made possible by Grants Number AR050520 and AR052345 from the National Institutes of Health (NIH). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Institute of Arthritis and Musculoskeletal and Skin Diseases (NIAMS), or the NIH.

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