Motion of the Human Hand

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Abstract

Background: The hand is complex, in that any small disturbance to the flexor tendons, extensor tendons, and intrinsic muscles can result in dysfunction of the entire structure. We designed a robotic device to consistently load a native thumb carpometacarpal (CMC) joint in assessing the effects of ligamentous damage on stability of the thumb CMC joint.

Methods: The device consisted of a mechanical plate in which to fixate a cadaveric hand, a tendon-suture routing system, a bracket to couple multiple suture lines to a cable to maintain equal force among sutures and tendons, and the finger-thumb force measurement devices. To apply force to the sutures, a cable was run from the suture coupling device to the tendon actuator and from the finger-thumb force measurement devices to the control system. The device was controlled using a Beaglebone Black microcontroller, load cells, rotary encoders, and a liquid crystal display (ie, LCD) touchscreen interface.

Results: The design worked as intended in terms of basic communication, signal processing, and control functions. Cyclic loading resulted in web creep of the tissue. Using closed-loop control, the system was able to settle to a desired load.

Conclusions: Use of the current device may result in improved understanding of joint movement within the hand, which may help surgeons in treating associated injuries. Future revisions to the device will aim to improve the hardware and software to accelerate the time to converging to the desired force and displacement.

Introduction

The hand is one of the most common sites of upper extremity injury and impairment, ranging from traumatic bone and soft-tissue injuries to chronic conditions such as joint osteoarthritis. The flexor tendons, extensor tendons, and intrinsic muscles work together in delicate balance to allow the fine movements of the fingers and thumb. Although it is clear that any small alteration in this delicate balance may lead to dysfunction of the hand, joint movement of the thumb carpometacarpal (CMC) joint is poorly understood.

Because the hand is a complex, balanced, and mechanical-based structure, reproducibility of the dynamic motion of the thumb CMC joint is difficult. To date, no studies have been successful in accurately and consistently simulating the physiologic motion of the hand in a laboratory. However, a clear understanding of joint kinematics is essential for assessing the effects of ligamentous damage and laxity on stability of the thumb CMC joint and determining possible involvement of mechanical-based instability in the development of thumb CMC osteoarthritis. Previous studies have relied on in vivo and cadaveric models to investigate possible change in metacarpal motions of the hand under loads of varying force.[1-4]

To help improve existing methods used for reproducing the motion of joints in the hand, we designed a device that uses high-fidelity measurements of the actual force of applied loads and amount of displacement to implement closed-loop control. That is, the apparatus automatically simulated the desired amounts of force and displacement.

Methods

System Architecture

The device consisted of two plates. The "dirty" plate included pulleys and components to fixate a cadaveric specimen, which could attached to an aluminum optical breadboard. Furthermore, the structure could be easily cleaned and sterilized. The "clean" plate consisted of the electronics and was located at a safe distance from contaminants. The forces generated by the actuators on the clean plate were transmitted by a standard, disposable cable wire, allowing a technically simple and low-cost operation. Cables were also used to relay the mechanical motion of a grip-force sensor (Figure 1).

A key feature of the design was its modular nature, which provided expandability in the number of degrees of freedom employed. Additionally, a single actuator could be used to apply a uniform load and displacement to more than one tendon by using one of several custom brackets that divided the actuator output.

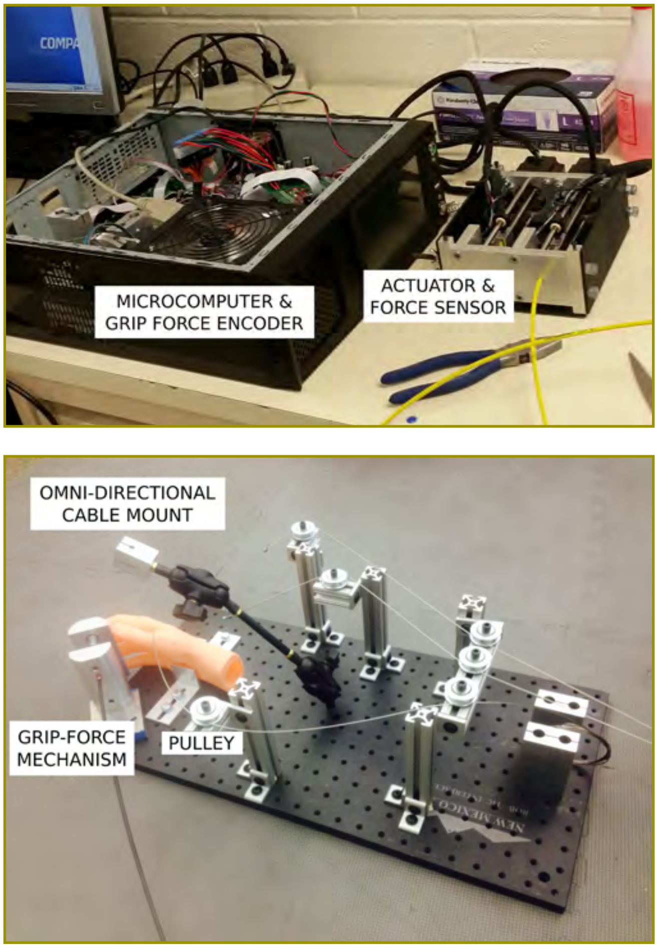

Figure 1. The designed device, capable of applying independent and uniform amounts of load and displacement to the tendon, showing two subsystems connected exclusively by disposable mechanical cables. (Top) The "clean" side, with the computer, sensors, and actuators. (Bottom) The "dirty" side, with fixture-based components and cable routers that can be sterilized.

Data Acquisition and Control Components

The electronics package consists of a standard computer power supply, a customized printed circuit board (PCB), and a BeagleBone Black (BBB) Rev. C microcomputer (Oakland Township, MI). The PCB was designed as a BBB cape and contained the motor drivers of the actuator, force-sensor filter, amplifier subsystem, and other necessary circuitry-related parts. The custom PCB and BBB allowed for a compact form factor and control of the motors, liquid crystal display (LCD), peripheral devices, and the sensors. All measurements were recorded and output as a single comma-separated values (CSV) file. The advantage of this was that recorded data could be post-processed with little difficulty.

The microcomputer (running a Debian Linux software) was controlled remotely by use of a Secure Socket Shell (SSH) connection, which can be achieved using a Universal Serial Bus (ie, USB) cable or connection to an ethernet network. The system could also be controlled using a built-in screen or a localized keyboard and mouse if an external computer and network connection were unavailable or not desired. The software ran a Graphical User Interface (GUI) built on a custom graphics framework that allowed the device to be controlled from any device that could run an X Windows server, including tablets and other handheld machines. The software and GUI framework were all programmed in the C programming language. The code and software were hosted on Github (ie, a repository hosting service for management of source codes) to allow optimal performance and testing across different platforms. Additionally, new releases of code could be easily updated to the device.

Actuator Design

The system included two actuator units. The actuators were placed outside of the computer case and chasis (ie, outer structural framework) in individual modular actuator assemblies, which each consisted of a frame, stepper motor actuator, force sensor, and bicycle cable fastening hardware. The stepper motor had the ability to pull at forces greater than 900 N (200 lb). The actuator drivers provided power to the stepper motor coils, which was provided by an amplified signal from the microcontroller. Actual force was measured using a Futek (FSH00096) load cell, with a range of 0 to 112.5 N (25 lb). In experiments targeting higher levels, alternative models of the same sensor could be used.

Results

Figure 1 shows the complete construction of the system. Basic communication, signal processing, and control functions of the device worked as designed. Preliminary efforts to calibrate the system included relating the amount of displacement of the grip sensor to the mount of force and characterizing nonlinearities in the system (eg, caused by frication and saturation of the electronic components).

Results of testing with a cadaveric specimen revealed that cyclic loading resulted in eventual elongation of the tissue, or tissue "creep." However, use of the closed-loop control allowed the system to settle to the desired load (Figure 2).

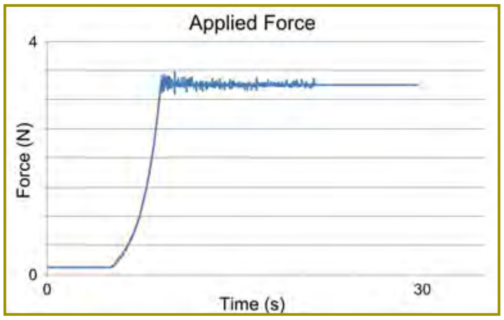

Figure 2. Data obtained from the force sensor after one actuator ramps up to a target load. Closed-loop control of the device ensures that the target load can be reached accurately.

Discussion

The current device was designed to pull at a set amount of force or displacement, which can be ideally used for testing resultant forces caused by pull of the tendons. However, owing to the mechanical operation of the device, the possible uses are not limited to biomedical-related research. Use of the device may also allow effective testing of biological tissues (eg, ligaments), investigation of non-biological filament strength, evaluation of polymer elasticity, and development of stress and strain curves.

In designing the current device, we aimed to facilitate novel research on biomechanics of the hand. The subsequent knowledge may result in improved reproducibility of cadaveric-based research, which often cannot be done in vivo. Better understanding of joint movement and ligament contribution to stability of joints may provide insight into effective methods for surgically treating patients with traumatic and degenerative conditions of the hand. Future work on the device will entail revisions of hardware and software to accelerate the time to converging the desired amounts of force and displacement.

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Conflict of Interest

The authors report no conflicts of interest.

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