Additive Manufacturing and Series Elastic Actuation for Hand Exoskeletons

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***Abstract*—Rehabilitation of the upper extremities, especially the hands, is critical for the restoration of independence in activities of daily living for individuals suffering from hand disabilities. There are currently two major challenges in developing robotic devices for hand rehabilitation: (1) design of a device that is compatible with the complex geometry and nonlinear biomechanics of the human hand and (2) actuation and control that leads to effective therapy through the exchange of suitable motion and forces between the device and the hand. We present the use of an additive manufacturing technique called Selective Laster Sintering for quick prototyping and a miniaturized series elastic actuator for force control of hand exoskeleton joints. We present the torque control results from experiments with an index finger exoskeleton, which is prototyped using additive manufacturing and is actuated by Bowden-cable-based series elastic actuators. Results showed that the device can be controlled to achieve accurate exoskeleton joint torque tracking while being highly customizable.**

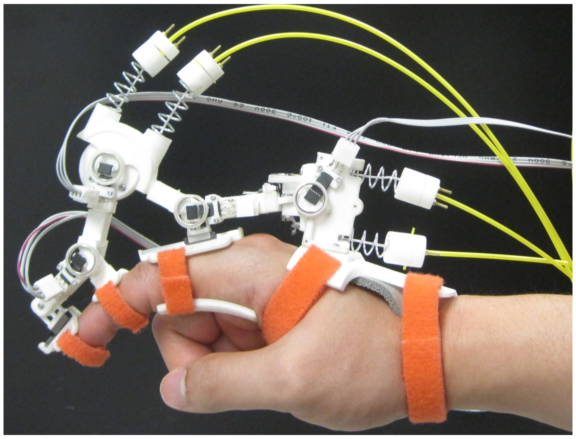

Fig. 1. A 3D printed and torque controlled index finger exoskeleton prototype mounted on a subject's hand for experimentation.

I. INTRODUCTION

OVER 19.9 million people in the US suffer from a disability of physical function of the upper body and have difficulty lifting or grasping [1]. Rehabilitation with robots has the potential to provide effective therapy to disabled individuals while making a quantitative assessment of recovery. Clinical trials have shown that robot-aided hand therapy results in improved hand motor function after chronic stroke with increased sensorimotor cortex activity for practiced tasks [2]. However, designing hand exoskeletons that could be effective for rehabilitation therapy is challenging. Current challenges in developing hand exoskeletons that could provide effective therapy to subjects include design of a device that is kinematically and dynamically compatible to the complex geometry and nonlinear biomechanics of the human hand and actuation and control that leads to effective therapy through the exchange of suitable motion and forces between the device and the hand.

Developing hand exoskeletons requires several iterations for refining design to ensure the kinematic and dynamic compatibility of the device with the hand. We present the use of additive manufacturing to help leverage hand exoskeleton design by providing a means to quickly prototype a design in a cost-effective manner while retaining the flexibility to modify it at a later stage. Also, research over the past decade has shown initial evidence that force-control based strategies (e.g. impedance, admittance, assist-as-needed) can be more effective for rehabilitation of both the upper and lower limbs than pure position-control [3]. However, these techniques have not been employed for hand exoskeletons due to lack of effective miniaturization of the force-control technology. We present the use of series elastic actuators to achieve stable and accurate force control of hand exoskeletons.

We present an index finger exoskeleton [4] that is manufactured using an additive manufacturing technique and is torque controlled using a miniaturized and compact Bowden-cable-based series elastic actuator.

II. ADDITIVE MANUFACTURING

We used Selective Laser Sintering (SLS) [5] for manufacturing the various parts of the developed index finger exoskeleton prototype using Nylon 11 (Fig. 1). This additive manufacturing method allowed us to print small and intricate components, while keeping them strong and light in weight. Since size, rather than complexity, determines the cost for SLS (as opposed to complexity more than size, for conventional machining), SLS was a particularly cost effective manufacturing solution for our prototype. SLS was also advantageous in that it allowed us to design components that serve multiple functions (e.g. housing for magnets of the angular position sensor and SEA springs were integrated with the links). This helped us in reducing both the number and size of components in the design. Furthermore, the printed components were highly machinable allowing for post-processing needed for accurate dimensioning of critical parts and also for required

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subject specific customization (if any). In addition, since this method allowed for quick manufacturing of the parts, it significantly reduced the development time of the prototype, leading to quick iterations of design and testing. However, we used machined metal components for some of the small and critical load bearing parts to ensure durability of the device. We believe that with the advancement in scanning technologies, quick scanning of a subject's hand and fast prototyping of the device with customized attachment interfaces could provide highly ergonomic design, which could help in improving the effectiveness of the therapy.

III. SERIES ELASTIC ACTUATION

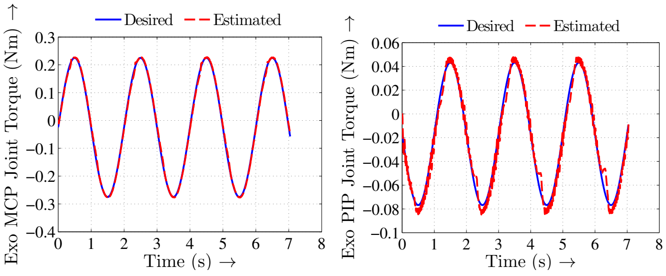
Series elastic actuators (SEA) provide a means to achieve accurate and stable force control with high backdrivability, low reflected inertia, and comfortable and safe interaction with the device. There have been a few attempts of introducing series elastic actuation in wearable lower extremity exoskeletons [6]. However, the constraints on space available on hand makes it challenging to introduce series elastic actuation in hand exoskeletons.

We developed a miniaturized and compact Bowden-cable-based SEA with remotely located actuators. The friction characteristics of the Bowden cable were nonlinear and dependent on the cable sheath configuration, cable length, velocity, pretension, and material combination of cable and sheath (stiffness and coefficient of friction). To overcome this nonlinearity, we placed the stiffness element closer to the exoskeleton joint and based on the measurement of the deflection of the stiffness element and the known stiffness value, an accurate estimate of the tension in the cable was obtained, which was then used for accurate bidirectional torque control at the exoskeleton joint. This also decoupled the motor inertia from the device and made the system backdrivable. However, limited space made it difficult to directly measure the linear displacement of the elastic element using linear potentiometers. Thus, we measured the displacement of the actuator and the exoskeleton joint and estimated the deflection of the elastic element using the relative displacement of the two, which is found to be fairly accurate at the operating cable tension as verified on a test rig [4]. Also, the magnitude of the torque range generated at the joint for the same range of actuator displacement can be adjusted based on the magnitude of the stiffness employed. Thus, choosing the correct stiffness ensures that only appropriate forces can be applied on finger phalanges making the device both safe and comfortable. In addition, the Bowden-cable-based actuation mechanism allowed for remote actuation without constraining the subject's hand to a fixed anchor or adding any resultant forces on the exoskeleton base.

IV. JOINT TORQUE CONTROL

The exoskeleton joint torque control was implemented on the actual prototype using the series elastic actuators to test the exoskeleton joint level torque tracking performance. We used the phase and mean shifted sinusoidal trajectories as the desired torque input to the system (1).

$$\tau_{jd} = \tau_{jA} \sin\left(2\pi f t + \phi_j\right) + \tau_{j\mu} \tag{1}$$



(a) (b)

Fig. 2. The exoskeleton joints torque tracking results from the prototype. (a) Exoskeleton MCP joint torque trajectories and (b) exoskeleton PIP joint torque trajectories.

where τ_{jd} is the desired joint torque, τ_{jA}, f, ϕ_j and $\tau_{j\mu}$ is the amplitude, frequency, phase and mean of the sinusoidal torque trajectory. The values of various parameters in the desired trajectories were determined experimentally so as to generate large range of motion at the two exoskeleton joints. The results showed that the controller was able to track the desired torque satisfactorily well (Fig. 2(a) and 2(b)). However, some noise was observed in the estimated torque trajectories due to the residual noise in the filtered exoskeleton joint angle sensor data.

V. DISCUSSION

We have introduced additive manufacturing and series elastic actuation in the design of hand exoskeletons for rehabilitation. The developed index finger exoskeleton showed good kinematic and dynamic compatibility with the human finger. Our control experiments with the prototype showed that effective bidirectional joint torque control can be achieved using the miniaturized series elastic actuators. In addition, ability to perform force control within the limited space will also enable us to implement other advanced control techniques such as impedance and assist-as-needed control on the device. We envision that with the pervasiveness of 3D printing technology in the future, rapid customization of the design to a specific patient in a clinical setting will become a reality, which could improve both the ergonomics and performance of the device.

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