Design and Analysis of a Parallel Haptic Orthosis for Upper Limb Rehabilitation

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Abstract— **The general design motivation for orthoses acting in parallel with a human limb is to improve human locomotion capability, develop joint strength, and increase endurance through physical rehabilitation exercises for the human limbs. The development of such rehabilitation devices improves the quality and frequency of physical rehabilitation exercises that a patient has to undergo during treatment. This paper describes the design of a grounded hand and arm rehabilitation orthosis. The orthosis provides bi-directional haptic feedback to the arm and joints of the fingers and the novel dynamic counterweight balancing mechanism prevents the effects of loading on the user's arm.**

Keyword- orthosis, upper limb, rehabilitation, human machine interaction, cable-driven, parallel exoskeleton

I. INTRODUCTION

Orthoses are defined as mechanical devices that are essentially anthropomorphic in nature, are 'worn' by an operator and fit closely to the body, and work in concert with the operator's movements. 'Orthosis' is typically used to describe a device that is used to assist a person with limb pathology [1]. Haptic orthoses of arm and finger joints find large-scale application in physical rehabilitation for patients suffering limited mobility of limbs after a stroke or cerebral damage and other joint ailments such as carpal tunnel syndrome. This type of hand and arm rehabilitation system facilitates repetitive performance of task specific exercises for patients recovering from neurological motor deficits [2][3].

Latest studies in neurology shows that the human brain has an ability to recover quickly and is capable of adapting after undergoing a stroke. Robotically assisted rehabilitation offers interactive, innovative, and precisely reproducible therapies that can be performed for an extended duration and be consistently implemented from site to site [2][4]. Rehabilitation using haptic orthoses is generally well tolerated by patients, and has been found to be an effective adjunct to therapy in individuals suffering from motor impairments, especially due to stroke. Existing orthotic device designs have certain limitations. There are no current haptic systems for training both hand and. Integrated whole arm activities are difficult because most orthoses are designed for upper arm motion and not for grasp and fine motor activities. The design challenges in building orthoses are in keeping a low power-to-weight ratio, and preventing the dynamic load of the device from acting on the limb during physical activity, its nonlinear behaviour and slow response. In an attempt to reduce the effect of the afore mentioned factors causes reduction of the forces experienced on user's the arm to a lesser range. Hence to overcome this most recent orthoses are grounded to support excessive weight [5].

A. Related work

Herr has discussed exoskeletal and orthotic devices that do not transfer substantial load to the ground, but simply augments joint torque and work. This type of exoskeleton could improve walking and running metabolic economy, or might be used to reduce joint pain or increase joint strength in paralysed or weak joints [6]. MIT Bio-mechatronics Group developed a powered ankle-foot orthosis to assist drop-foot gait, a deficit affecting many persons who have experienced a stroke, or with multiple sclerosis or cerebral palsy, among others [7]. These devices are low on weight and are useful as active orthosis and permit locomotion. Better control of mobility is provided by hybrid assistive system (HAS), as mentioned by Popovic et. al., using a combination of functional electrical stimulation and self fitting modular orthosis (SFMO) [8]. Kiguchi et. al. have developed an upper limb orthosis which is capable of providing flexion- extension and abduction- adduction exercises for the arm operating from an powered elbow joint [9].

Existing orthoses designs do not satisfy all the needs of physical rehabilitation. The device should be modular, lightweight, and easy to attach even to deformed hands [10]. Orthoses that are portable, easy to use and low on maintenance can play a vital role in developing countries that have a large number of patients that require physical rehabilitation treatment and the healthcare infrastructure and number of medical professionals is insufficient to meet the needs of the vast population.

This paper proposes the design of a orthosis which is self adjusting, modular and has a low power to weight ratio. Analysis of limb motion, first pioneered by Bernstein [11] has come a long way in terms of simulation packages and has be successfully used to analyse the effects of loading of the orthosis on the user's arm. Most current orthotic devices describe a static counterweight that is added for continuous gravity compensation that is inconsistent with the variations in load experienced during limb motion [12][13]. The orthosis we propose incorporates a novel dynamic counterweight balancing mechanism for consistent offloading of the user's limb.

II. SYSTEM DESIGN

The haptic orthosis described in this paper consists of 17 degrees of freedom, six of them being active bi-directional force feedback joints. The orthosis provides 3 degrees of freedom for each finger, controlled by a motor connected to the metacarpophalangeal (MCP) joints though rigid links, except the thumb that has four degrees of freedom. In addition to the degrees of freedom for the fingers it also provides one active haptic joint at the elbow for rehabilitation of the arm as shown in Figure 1.

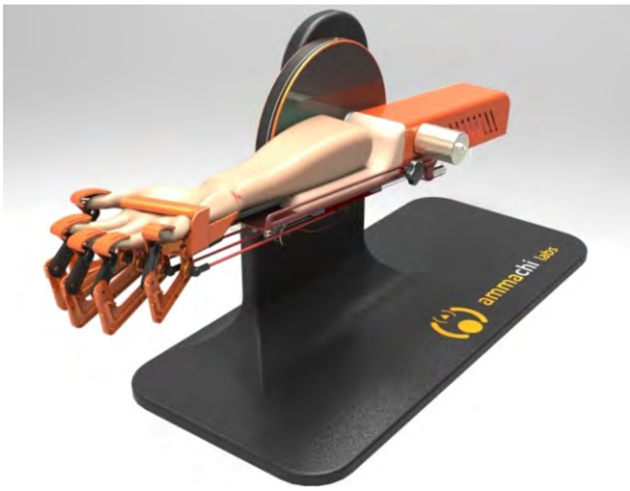

Fig. 1. 3D model showing placement of the hand and arm in the Haptic Orthosis

The force exerted on each of the fingers is limited by the control system that provides the actuation signal to the motors, depending on the maximum Force capacity of the human finger as shown in Table I below.

TABLE I
HUMAN FINGER FORCE CAPACITY

Finger	Joint	Angle Max. Min.	Max. Force (N) Continuous Max. force perpendicular to finger	Continuous Max. force in direction of Phalange
Thumb	MCP IP	0~90 0~90	15	35
Index	MCP PIP DIP	0~85 0~100 0~80	10	32
Middle	MCP PIP DIP	0~85 0~100 0~80	10	30
Ring	MCP PIP DIP	0~85 0~100 0~80	9	24
Pinkie	MCP PIP DIP	0~85 0~100 0~80	8	18

A. Design Factors

Maximum Force at fingertip: The average maximum force that can be applied perpendicular to the finger is 10N. For the study, we conducted some Monte Carlo experiments to estimate the force range that could provide acceptable performance.

Back drive Friction: It is important to keep the ratio of maximum force applied perpendicular to finger to back- drive friction as high as possible. In most cases there are at least three sources of back drive friction. Bearing friction, friction in the transmission and the friction generated within the actuators. The friction in the bearings and transmission can be reduced by proper selection of materials. In motor actuators that ratio is typically 30:1 for open loop control. The selection of brushless motors will also help reduce this effect.

Inertia: A portion of the resistance to movement felt by a user on their hand and arm is due to the inertia in the bearings and the inertia of the motor assembly. The reflected inertia of the motor is proportional to the transmission ratio, N, squared.

Backlash: A transmission with a backlash will cause the positional variation or 'slip' between the actual and sensed position at initial motion conditions. Ideally the system should have zero-backlash [14]. Typically a backlash of more than 0.254 millimetres is considered unacceptable, especially if a visual feedback mechanism is in the loop with the orthosis. The non-linear distribution of forces due to backlash also makes it difficult to control a virtual object.

Stiffness: The stiffness 'k' of the device is directly proportional to the rigidity of the links, and the frequency of the servo loop. The structural stiffness can be made very high by optimal design. The achievable maximum stiffness with the stable servo-loop is a function of inertia of the device, the impedance of the user's finger attached to the device, the transmission ratio, the servo rate, and the encoder resolution. From the above-mentioned parameters, transmission ratio tends to vary much easily [15].

Bandwidth: An important functional feature of the orthosis is its bandwidth, the frequency range within which it can receive the motion commands from the human operator and provide force feedback to the operator finger. The human hand has asymmetric input /output capabilities and the maximum frequency with which a typical human hand can transmit motion command to the orthosis is 15 to 10 Hz, whereas it demands that the position and force-feedback signals to be presented to it at a frequency not less than 12 to 30Hz. The earlier work by Bolanowski et. al. [16] indicates that feedback to the operator hand for force feedback continuity, is to be provided at no less than 500Hz in a typical task whereas a feedback frequency of 5 to 10 KHz of may be necessary in a precision task. It is clear that the bandwidth requirement depend up on the nature of the task.

B. Mechanical Design

The mechanical design of the orthosis is describes the mechanism for attachment to the hand and arm. The mechanical hand structure used to provide bidirectional force feedback to the each human finger. It has 3 degrees of freedom in the flexion and extension on the index finger, middle finger, ring finger, little finger and 4dof on the thumb at the metacarpophalangeal (MCP) joints, interphalangeal proximal (PIP) joints and interphalangeal distal (DIP) joints.

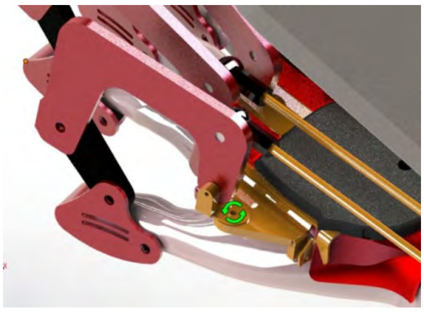

Fig. 2. CAD model of the 3-link serial mechanism for the thumb including flexion, extension, adduction and abduction

Although fingers have abduction and adduction as two additional degrees of freedom, it does not play a vital role in force feedback based rehabilitation for the fingers except for the thumb, and hence a additional degree of freedom for the thumb has been incorporated in design as shown in Figure 2. Stergiopoulo et. al. describe the use of a 3-link serial mechanism allows full finger flexion and extension [17]. This orthosis consists of a mechanism with an addition of a joint for rotation of the thumb phalanges. The distal phalanx of the each finger is fixed with link 1 in the 3-link serial mechanism as shown in Figure 3.

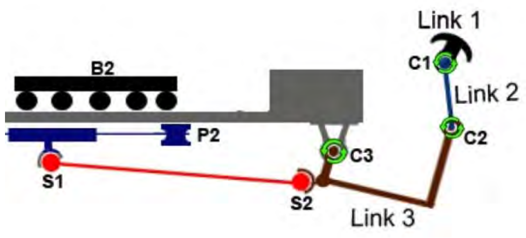

Fig. 3. Schematic of the 3-link serial mechanism for controlling the finger movements

To accommodate varying hand sizes, we provided proper spacing and angle between the each of the 3-link serial mechanism as shown in Figure 4. The angle between each joint and the horizontal is chosen in the range of adduction and abduction of each finger workspace of human arm to avoid the collision between the linkages.

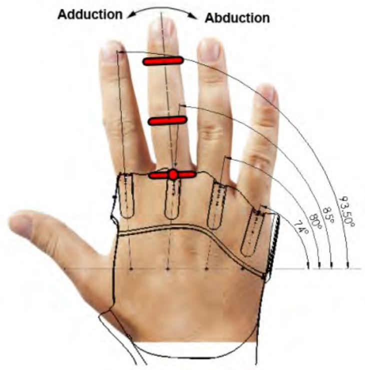

Fig. 4. Schematic showing placement and angular degree of freedom of the orthosis joints overlaid on a human hand

This design provides bidirectional force feedback in each fingertip at every position. Although use of cylindrical joints at the pivot joint S2 shown in Figure 3, will provide smooth flexion and extension motion, it suffers from insufficient space for varying hand sizes. Hence we designed the use of sperical joints to transfer the bidirectional force from a cable drive linear transmission system. The above-mentioned assembly is fixed on telescopic slide that helps users to adjust the system for a wide range of size variations in the arm, resting on a seat as shown in Figure 6. This assembly is attached to the large circular disc and this disc is pivoted on a base as seen in Figure 1.

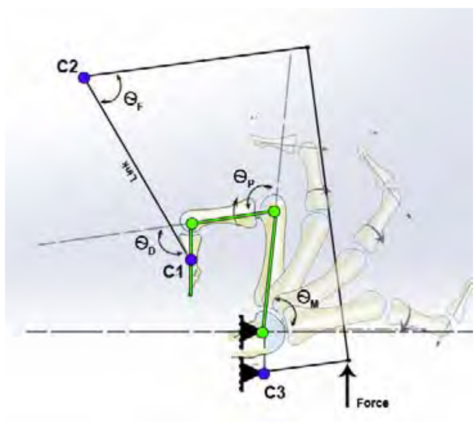

Fig. 5. Schematic showing angles described by the DIP, PIP and MCP finger joints

The coupled movement of flexion/extension of the PIP joint and DIP joint results in free finger movement. Hence the orientation of each phalange can be predicted by knowing the angle between the linkages. In the case of typical ball squeezing task we set the angle $_{F}$, shown in Figure 5, by activating the brake on the joint C2. $_{F}$ will differ for each user, Its taken by the homing condition set by the encoder at joint C2, when each user moves all the fingers to the maximum flexion condition. The point of joint C1 is located wr.t the XY plane and the line connecting the C1 to the finger base forms a 4-bar structure. By solving the kinematic equation [17], we can obtain the values of $_{D}$, $_{P}$, $_{M}$.

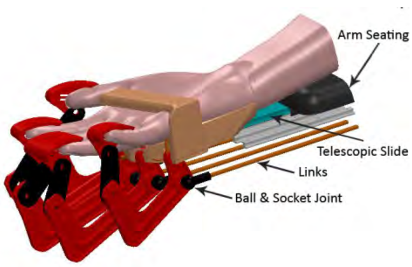

Fig. 6. Schematic showing the adjustable hand mechanism of the haptic orthosis

C. Transmission system

The transmission system design of orthosis is challenging since the human hand an arm require large torques to mobilise but at the same time, ergonomics and aesthetics require compact and low weight drives [18]. Every effort was made to keep the orthosis actuators are compact and lightweight. We selected brushed dc mini motors for the hand and a larger brushless dc motor to actuate the transmission system for the arm. It allows for large bandwidth and high force resolution, which is necessary for accurate active force transmission to the limb.

1) Transmission system for the hand

We chose Synchromesh cable drives for the transmission to provide high precision positioning of linkages. Synchromesh cables are light weight and have lower inertia, high strength, small bending radius and lower tensioning maintenance when compared to steel cables. They have zero backlash transmission specification and contribute very low friction. The synchromesh cable also requires lesser force application for pre tensioning when compared to a steel cable. Pretension tends add radial loads to the elbow joint assembly. The tension which a typical drive capstan can maintain on a cable is proportional to F_c x , where F_c is the coefficient of friction between the cable and capstan and is the number of degrees of the arc that the cable wrapped around the capstan describes. All the motors for five fingers are placed on one end, which is right angle to the linear axis of movement. The transmission system of the hand is shown in Figure 7. and Figure 8.

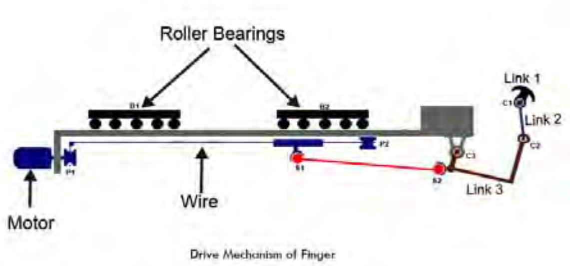

Fig. 7. Schematic showing the transmission system for the hand assembly of haptic orthosis

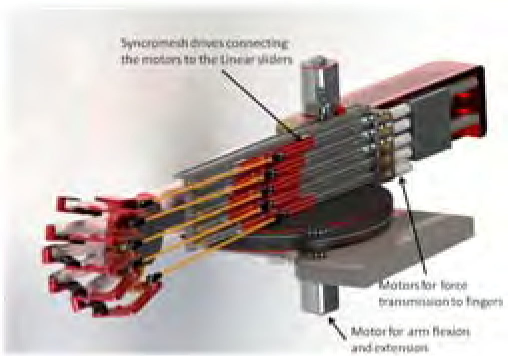

Fig. 8. 3D model showing the transmission system for the hand assembly

2) Transmission system for the arm

The most critical selection criterion for the transmission system for the arm is to avoid backlash in the large gear ratio mechanism required to deliver torques to the arm. We examined several gear reduction techniques and narrowed down to the typical capstan drive mechanism that is the only method that is commonly used in commercial haptic devices and provides zero backlash. But in the case of the orthosis we have designed, the typical cable drive fails due to less friction between wire and capstan at a large torque conditions. A solution to this is the use of synchromesh cable drive similar to the ones used in the hand mechanism. The weight of the typical forearm and hand is 15N [19][20]. The elbow joint is closely aligned with the pivot axis of the orthosis. Typically, in an assembly as shown in Figure 9, the motor would have to apply a torque 'τ_a' to overcome the torque 'τ' due to moment that developed on the pivot axis due to the weight of the arm acting with a force F. To lift the arm, under such a condition would require high gear ratio. But higher gear ratios limit the dynamic range for force-feedback.

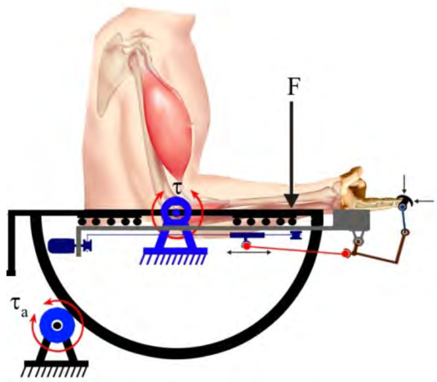

Fig. 9. Transmission system for the Arm portion of Haptic Orthosis

Higher gear ratio also multiplies the armature resistance of the motor adversely affecting the force-feedback.

3) Transmission system for Dynamic Counter Weight

To overcome the above-mentioned issue of loading on the motor in the arm force feedback assembly, we propose a novel dynamically counterbalanced weight mechanism. That will reduce the torque τ on the pivot axis to close to zero. Dynamic counterweights are the weights that move linearly to compensate for loading effects in a system. Its position is controlled by a control system that measures the torque τ experienced at the pivot joint.

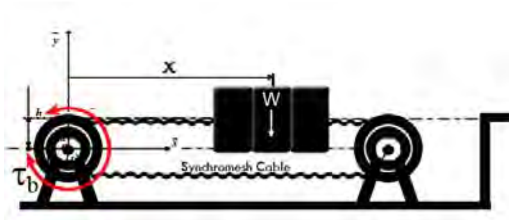

Fig. 10. Schematic describing the transmission system for the dynamic counterweight mechanism

The transmission system shown in Figure 10 must be capable of providing an aggressive response to move the counterweight "W" without any delay. It must have also have zero backlash for accurate control of the counterweight position. The movement of counterweight in the plane on which the arm rests neutralizes the unbalanced forces in the plane. The torque τ_b is the control signal applied to the motor for dynamic counter weight balancing. A synchromesh pulley is directly coupled with the motor and this pulley drives counterweight using the synchromesh cable of which the two open ends are fixed on the weight.

III. SYSTEM ANALYSIS

We performed a multi body dynamics simulation to analyse the response time for the finger linkage of the orthosis. This also allowed us to estimate the forces acting at the joints at any time during the dynamic transient. The total solution time is measured in seconds and all parts are assumed to be infinitely stiff. To analyse the performance of the finger linkage when the motor actuating the joint is accelerating, we applied a tabular continuous data set of remote forces on the Linkage L3 over time and the subsequent acceleration of the body & joint forces were plotted.

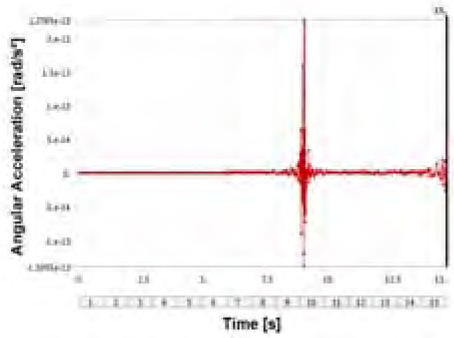

Fig. 11. Plot of acceleration over time of the rigid finger linkage for the index finger

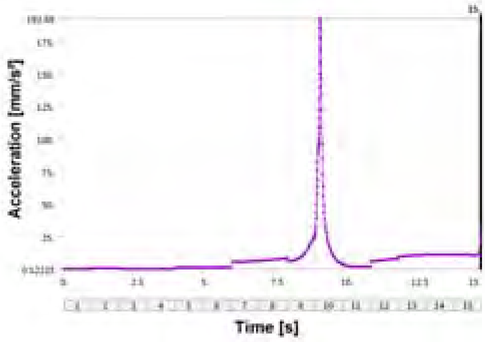

Fig. 12. Plot of acceleration over time experienced by the Distal Phalanx of the index finger

When compared with the plot of the acceleration of the linkage driven by the motor shown in Figure 11, the acceleration of the distal phalanx is instantaneous with an average approximate delay of less than ±0.03 secs.

The average force experienced at the DIP, PIP and MCP joints as shown in plots in Figure 13, 14 and 15 are approximately equal to 2 e-2 ± 0.06, from which we can infer that the orthotic linkage mechanism for the finger distributes the force exerted by the actuator evenly over the three joints of the finger and is sufficiently less than the maximum rated force that the finger can tolerate.

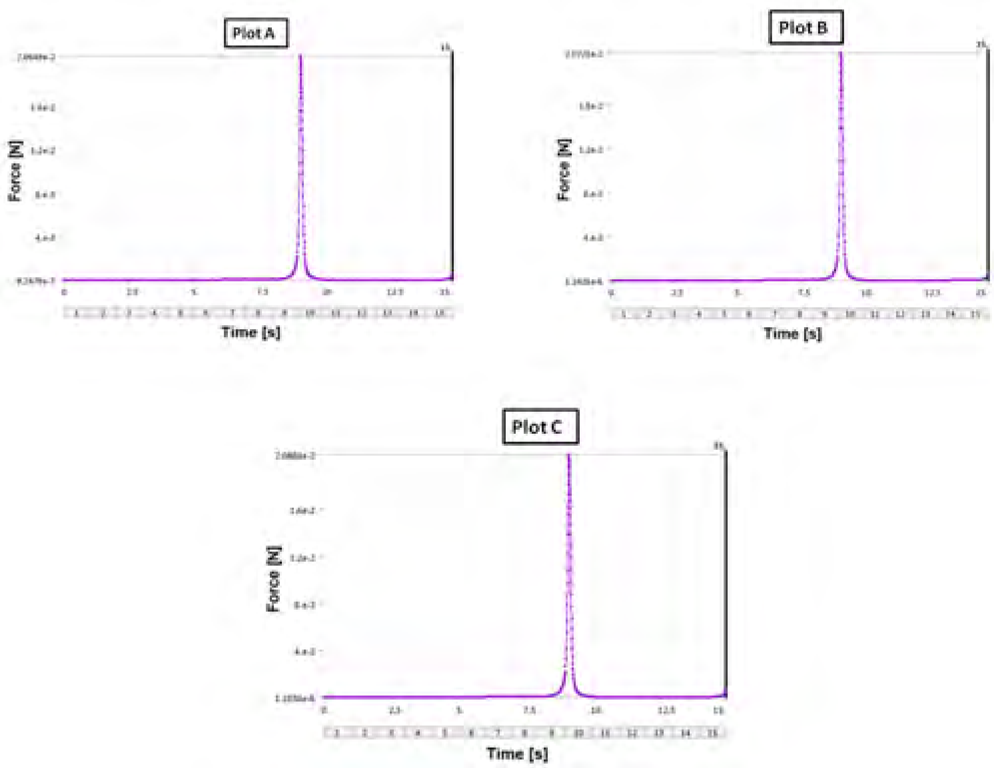

Figure 13. Plot A of DIP, Plot B of MCP and Plot C of PIP, show the force experienced by the joints when under acceleration

IV. CONCLUSION

The haptic orthosis provides sufficient response and force resolution required for smooth motion synthesis required for human hand and arm rehabilitation. Such a design can be extended beyond rehabilitation augmented with virtual reality and augmented reality simulations [21] for applications such as computer games, haptic perception experiments, human motion and musculoskeletal response studies to name a few. It can also be extended to other applications as an exoskeleton. There is scope for further enhancements in design to incorporate degrees of freedom for the wrist rotation, abduction and adduction.

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