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DESIGN OF A HAPTIC ARM EXOSKELETON FOR TRAINING AND REHABILITATION

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ABSTRACT

A high-quality haptic interface is typically characterized by low apparent inertia and damping, high structural stiffness, minimal backlash and absence of mechanical singularities in the workspace. In addition to these specifications, exoskeleton haptic interface design involves consideration of additional parameters and constraints including space and weight limitations, workspace requirements and the kinematic constraints placed on the device by the human arm. In this context, we present the design of a five degree-of-freedom haptic arm exoskeleton for training and rehabilitation in virtual environments. The design of the device, including actuator and sensor selection, is discussed. Limitations of the device that result from the above selections are also presented. The device is capable of providing kinesthetic feedback to the joints of the lower arm and wrist of the operator, and will be used in future work for robot-assisted rehabilitation and training.

INTRODUCTION AND MOTIVATION

Recent advances in the field of robotics have led to fast developments in the field of haptics [1–3]. Haptics refers to the use of robotic interfaces for force feedback in human-computer interaction. Haptic or force-reflecting interfaces are robotic devices used to display touch or force-related sensory information from a haptic environment to the user.

Based on the point of attachment of the base of the robotic interface, haptic display devices can be classified as grounded [4] or ungrounded [5]. A grounded haptic device is affixed to a rigid base, while ungrounded haptic devices are attached on the body of the operator itself. As the name implies, a grounded haptic device transfers the reaction forces to the ground, whereas an ungrounded device exerts reaction forces on the user at the point of attachment(s). Typically ungrounded haptic interfaces are good at providing tactile feedback such as grasping forces during object manipulation. Alternately, grounded devices perform better when displaying kinesthetic forces to the user, like forces that arise when simulating static surfaces [1]. A grounded device also has a limited workspace as compared to an ungrounded one. The increased workspace for an ungrounded device is achieved at the expense of design simplicity.

The ability to interact mechanically with virtual objects through incorporation of haptic feedback allows users to manipulate objects in the simulated or remote environment with ease when compared to a purely visual display. This makes a haptic display suitable for a variety of applications like remote operation in hazardous environments and simulators for surgical training [6–8]. Added advantages of haptic simulators include increased repeatability, scalability, safety and control over environmental conditions. The user can also be conveyed information about physical attributes of the simulated objects, like hardness, texture or inertia through haptic feedback. It is also possible to simulate additional physical forces and fields, which may or may not be part of a natural environment, in order to convey information to the user. Due to the above-mentioned reasons, an applica-

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tion for which haptic feedback has attracted attention is rehabilitation research [9–11]. Physical therapy utilizing the resistance offered to user's motion during haptic interaction can be used for rehabilitation of impaired arm movements in patients. Furthermore research has shown that augmented feedback presented in virtual environments accelerates the learning of motor tasks [11], making this another appealing application of haptics.

Prior Work

A force-feedback exoskeleton is a haptic device worn by the user. Arm exoskeletons help to simulate large forces at the hand or arm, like the weight of an object that is held. This is achieved by providing feedback to the various joints of the arm - the shoulder, elbow and wrist. Although worn by the user, the device itself may be a grounded one in which case it restricts user mobility.

In recent years, improvements in sensing and actuation technologies, control systems and computing resources have led to development of many successful haptic interfaces. Although a large number of high performance hand controllers have been successfully fabricated, research in design of exoskeletons for other parts of the body is still in an early phase. Burdea provides a nice discussion of early stages of the development of exoskeletons [1].

The first modern exoskeleton arm/glove was designed and developed at ARTS lab, Italy for replication of sensations of contacts and collisions [4]. The ARTS arm, also known as the PERCRO exoskeleton, is a 7-DOF ungrounded device, attached to operator's shoulder and torso. The operator holds onto the device with his/her palm. Hence, the device can only exert forces at the palm of the user. It uses DC motors with a cable transmission system for actuation. A 9-DOF under-actuated exoskeleton arm developed at Korea Institute of Science and Technology (KAIST) by Lee et al. addressed the workspace issues associated with the PERCRO exoskeleton. The device allows for full reproduction of the human arm's workspace when operating the exoskeleton [12]. The wearable Salford arm, developed by Tsakarakis et al. in 1999 addresses some of the issues posed by earlier designs [5]. Almost ninety percent of the human arm's workspace can be replicated with this design. The pMAs though have a highly non-linear behavior and a slow response, thus presenting control challenges. Another exoskeleton developed at KAIST addresses the issue of wearability of their previous design by using parallel mechanisms and pneumatic actuators [13].

Most of the earlier exoskeleton interfaces attempt to optimize one or more of the following characteristics of the haptic system, namely power to weight ratio [5,12,13], workspace [12], wearability [13] or stability and control bandwidth [4, 14, 15]. Individual designs, however, achieve the optimizations at the expense of other useful features, usually workspace [4, 13, 14] or control bandwidth [5, 12, 13]. In this paper, we present work that combines the useful results from prior research towards the design of a high quality haptic interface with a reasonable workspace. This is achieved at the expense of added weight and decreased mobility due to device grounding. Figure 1 shows a subject operating the exoskeleton.

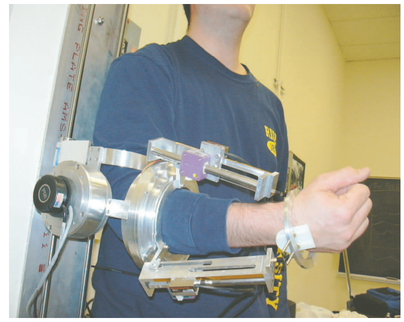

Figure 1. USER OPERATING THE EXOSKELETON

DESIGN FACTORS IN HAPTIC EXOSKELETON DESIGN

Haptic feedback aids the operator to reliably complete a remote or virtual task. Primary requirements for such a system are the ability to convey commands to the remote or virtual plant and to reflect relevant sensory information, which relates to forces in the remote or virtual plant, back to the operator. In essence, the dynamics of the device must not interfere with the interaction of the operator with the environment. This is directly related to the highest environmental stiffness that can be simulated without compromising system stability. An ideal haptic interface behaves as a rigid body, through which the user interacts with the environment, over the complete range of frequencies.

In practice, however, performance is limited by physical factors like actuator and sensor quality, device stiffness, friction, device workspace, force isotropy across the workspace, backlash and computational speed. Force isotropy, which refers to the equality of force exertion capability of the device in all directions, is important to ensure identical device performance across the workspace. The desired size and shape of the workspace itself is typically dependent on the target application(s) and serves as an important factor in determining device size and mechanism. Also of consideration in the design of haptic arm exoskeletons is the biomechanics of the human arm. The arm imposes a force/position constraint on the device thus affecting the system behavior and performance. The following sections discuss the different aspects involved in the design of haptic arm exoskeletons.

Biomechanics of Human Arm

The property that differentiates haptic human-computer interaction (HCI) from more common audio-visual modes of HCI is the bilateral transfer of both power and information signals

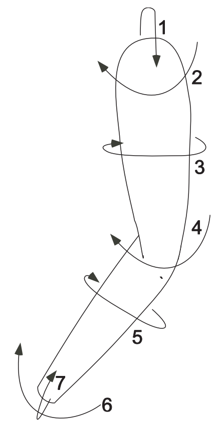

Figure 2. DEGREES OF FREEDOM OF THE HUMAN ARM

Table 1. WORKSPACE AND TORQUE LIMITS OF HUMAN ARM JOINTS. *Source: Tsagarakis et al. [5]

Joint	**Human Isometric Strength***	**Workspace**
Elbow Flexion/Extension	72.5 Nm	Flexion: 146° Extension: 0°
Forearm Supination/Pronation	9.1 Nm	Supination: 86° Pronation: 71°
Wrist Palmar/Dorsal Flexion	19.8 Nm	Palmar Flexion: 73° Dorsiflexion: 71°
Wrist Abduction/Adduction	20.8 Nm	Adduction: 33° Abduction: 19°

[16]. A part of the operator's body, typically the arm, is always part of the haptic control loop. The haptic device exchanges power as well as information with both the human and the virtual environment. The human forms a part of the control loop and hence imposes both dynamic and kinematic constraints on the interface.

During operation of a haptic arm exoskeleton, the arm biomechanics gain further importance due to the kinematic constraints placed by the human arm on the device. Figure 2 shows a simplified model of a human arm. The human arm has seven DOF: Abduction/Adduction[1] and Flexion/Extension of the shoulder[2]; Rotation of the upper arm[3]; Flexion/Extension of the elbow[4]; Rotation of the forearm[5]; and Radial/Ulnar deviation[7] and Flexion/Extension[6] of the wrist, as shown. It is desirable that the haptic exoskeleton does not compromise the natural arm motion and workspace of the operator. The device should also have torque capabilities to match and enhance human abilities. Table 1 shows the workspace and torque capabilities of the human arm.

Performance Related Design Parameters

A good quality haptic interface is characterized by, among other measures, stability bandwidth and transparency. The stability bandwidth refers to the range of frequencies of forces that can be reflected to the operator with the device, while ensuring stable system behavior. In a haptic simulation the human exchanges power with the haptic interface and hence, the human operator is capable of stabilizing an otherwise unstable system or destabilizing a stable one. Instabilities in a haptic system are highly undesirable as they can pose a threat to the device as well as the human. Research has shown that stability of a haptic simulation is related to the simulation rate, virtual wall stiffness and device viscosity [17].

Transparency is a measure of the degree of distortion between the force at the human-robot interface and the desired contact force as commanded through the virtual environment. Transparency can be degraded by such things as backlash, inertia or friction in the haptic device, sensor resolution and computational delay. Transparency is also related closely to the stiffness in the virtual environments as a transparent system should be able to simulate very high stiffness. Maximum virtual wall stiffness therefore, is sometimes used to characterize haptic device performance [18]. Factors that affect the stable and transparent behavior of a haptic interface primarily include sensor resolution and computational rate of the simulation apart from hardware characteristics discussed above.

Control Related Design Parameters

A haptic system applies trajectory dependent forces to the operator's body. This is typically implemented in one of two modes - the impedance control mode or the admittance control mode. During impedance control, the user commands motion to the haptic interface and the robotic device applies forces on the user's arm based on changes in the virtual environment. In the admittance control mode, the user applies force to the device which imposes motion on the user's arm.

The control mode used determines the backdrivability of the haptic device. Backdrivability refers to the property of a haptic device to be free to move in space when no forces are being displayed through it. A device designed to be operated using impedance control is ideally backdrivable and frictionless, whereas a device employing admittance control should be non-backdrivable. In the impedance control mode it is also desired that the device have minimal inertia to facilitate easy maneuvering. Furthermore, low inertia and friction improve interface performance by reducing forces required to compensate device dynamics. This becomes even more important in the design of exoskeletons as the device is normally carried by the user.

Summary of Design Considerations

It is apparent that haptic exoskeleton design involves various trade offs, which limit the device performance achievable while maintaining system stability. To summarize, the design aspects include: mechanism design which limits or affects human abilities; sensor and actuator selection that is directly related to the weight of the device, range of forces, stability and cost; and actuator placement and transmission as it affects the apparent inertia of the device. Hence, the design decisions are greatly influenced by the target application for the device.

Training and rehabilitation in virtual environments is typically implemented using virtual force fields for guidance [19] or active assistance [20,21]. This requires the robot to allow natural human arm movements, with minimal reduction in workspace of the human arm. Wearability of the device increases safety concerns and special care needs to be taken to ensure human safety. Furthermore, mobility of the interface is not normally a requirement for such a system. Hence, the device can be grounded to support excessive weight and gravity compensation implemented through the controller. Additionally, the slow frequency of human movements ensures that the inertia of the device plays a small role in its operation. Therefore, when designing an arm exoskeleton for training or rehabilitation, the kinematic design of the robot should be the prime consideration. In the following sections we document our design goals and present the current version of the exoskeleton design.

DESIGN OBJECTIVES

Table 2 shows the desired design specifications for the exoskeleton in terms of the range of motion of the human arm and torque display capability. While the workspace specification closely matches the average range of motion of human joints as shown in Table 1, the torque capabilities lag far behind human abilities. This is primarily due to limitations in current actuator technology and some practical restrictions on the size of actuators which can be used in a arm exoskeleton. The torques achieved by Tsagarakis et al., using a pneumatic muscle powered exoskeleton, have been used as target specifications for our design [5].

Research has shown that fairly low stiffness and force values are sufficient for object detection [22,23]. Therefore, if designing a haptic exoskeleton for teaching arm movements using virtual force fields, a low quality interface would suffice. In our case, as we want the device to be used as a general purpose training tool for arm movements, it is required that the device be able to simulate high quality virtual surfaces which are part of the operating environments. As a result, emphasis was placed on the design of a high performance interface which encompasses the human arm workspace. In addition, for rehabilitation applications, the ability to control feedback to individual human arm joints is desirable and has been addressed through this design.

Table 2. DESIGN SPECIFICATIONS FOR JOINT TORQUE AND MOTION LIMITS

Joint	Torque Specification	Workspace Specification
Elbow Flexion/Extension	6Nm	Flexion: 120° Extension: 0°
Forearm Supination/Pronation	5Nm	Supination: 90° Pronation: 90°
Wrist Palmar/Dorsal Flexion	4Nm	Palmar Flexion: 60° Dorsiflexion: 60°
Wrist Abduction/Adduction	4Nm	Adduction: 30° Abduction: 30°

THE MAHI EXOSKELETON
Basic Mechanism Design

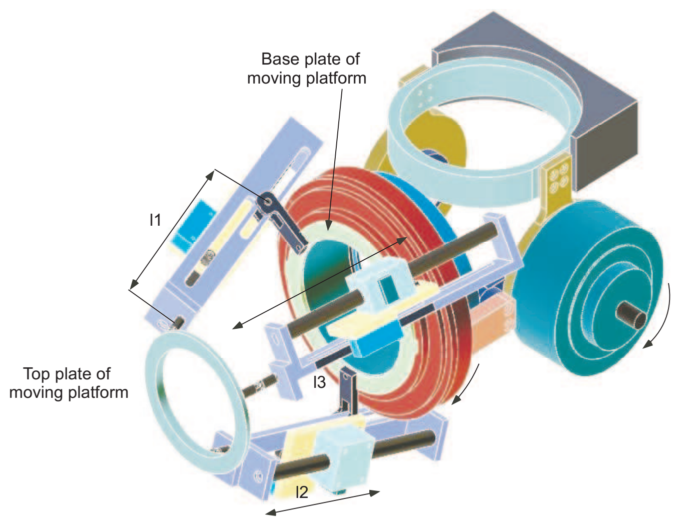

Figure 3. EXOSKELETON MECHANISM: A 3-RPS platform is used as the wrist of the robot. Joints R1, R2 and R3; and B1, B2 and B3 are located at vertices of equilateral triangles.

Figure 3 shows the assembly drawing of the five degree-of-freedom exoskeleton. The exoskeleton is comprised of a revolute joint at the elbow, a revolute joint for forearm rotation and a 3-RPS serial-in-parallel wrist. The 3-RPS platform, first introduced by Lee and Shah, consists of two platforms connected by three prismatic links, $l1$, $l2$ and $l3$ [24]. Each link is connected to the base through a revolute joint and to the top plate using a spherical joint. The rotary and spherical joints are located at vertices of equilateral triangles on their respective plates. This platform has three degrees-of-freedom, with actuated prismatic joints, two in orientation and one in translation. The height of the platform allows for adjustment to forearms of different lengths and is kept constant during operation. It should be noted that the platform has limited movement transverse to the vertical axis through the base and no singularities for $\theta_i \in (0, \frac{\pi}{2})$ [24], where θ_i is the angle between the prismatic link li and the base platform.

During operation, the robot is worn so as to line up the elbow joint of the robot with the operator's elbow joint and the top plate of the wrist of the robot with the wrist joint of the operator. This configuration aids in preserving natural arm movements by aligning the robot's kinematic structure with that of the human arm. The mapping between the robot configuration and arm position is also simplified by the use of this kinematic structure for the robot. There exists a one-to-one mapping between human wrist joint angles and the *xyz* Euler angle representation of the orientation of the top plate of the platform.

Kinematic Design of the Wrist

The 3-RPS platform used as the wrist platform involves several design parameters which affect the workspace of the device. These parameters include the ratio of the radii of the top and base platforms, ρ, the link travel, maximum link length and the height of the platform. These parameters were calculated using the sequential quadratic programming algorithm, in order to optimize the wrist workspace for $\pm 60^\circ$ rotation in pitch and $\pm 30^\circ$ in yaw. The algorithm is implemented through the `fminimax` function as a part of the MATLAB© optimization toolbox.

For workspace optimization, ρ and the height of the platform in the initial configuration were optimized. It should be noted that in this application the height of the platform is maintained constant during operation as only the two degrees of freedom in orientation of the top plate are used. The cost function used for minimization was

$$f(x) = L_{max}^2 + (L_{max} - L_{min})^2. \quad (1)$$

where L_{max} and L_{min} are the maximum and minimum link lengths over the entire workspace of interest. This cost function thus minimizes a weighted sum of the maximum link length and link travel.

Sensing and Actuation

Sensor Selection Sensor resolution affects the range of frequencies of forces that can be displayed by the haptic interface and hence the display of detail from an virtual environment. This is directly related to the quality of the interface. Consider for example, the simulation of a thin virtual wall. If the sensor resolution or the computational speed is not high enough then there exists a possibility that the human can pass his/her arm through the wall without feeling the force. Furthermore, during simulation of stiff virtual surfaces, reduction in sensor resolution increases the delay in sensing human's actions in the virtual environment and this delay can decrease system stability. Hence, high resolution optical encoders were used for the device.

Following these guidelines the forearm joint uses a custom Mercury 1500 encoder system from Micro-E Systems, which provides a resolution of 0.002°. RGH-24 series encoders from Renishaw with a liner pitch of 1um have been used for the linear axes.

Actuator Selection The actuators for a haptic device determine the range of magnitude and frequencies of forces that can be displayed with the interface. To reproduce real-life situations it is desirable that the device be able to display forces in a large range of magnitudes as well as frequencies. In order to limit device inertia, high power-to-weight and high bandwidth are desirable qualities for actuators used for a haptic interface. The bandwidth refers to the response time of the actuator and thus directly impacts the range of freqencies of forces that can be displayed.

No single actuator technology provides the benefit of both high power-to-weight and high bandwidth. Pneumatic actuators are inexpensive and provide the benefit of high power-to-weight ratio. But, pneumatic actuators have a low bandwidth, which limits their utility as actuators for haptic interfaces. Continuous force control of pneumatic actuators also involves the use of servo valves and compressors, which are fairly expensive. Tsagarakis et al. used pneumatic muscle actuators for their exoskeleton, due to their muscle like properties [5]. These actuators, however, have highly non-linear dynamics in addition to low bandwidth making them unsuitable for application in haptic devices. After consideration of the above-mentioned facts, electrical actuation was chosen for the robot. Electrical actuators have a lower power-to-weight ratio but a very high bandwidth. This increases the weight of the device but allows for better force reflection through the interface.

Following are the specifications of the selected actuators (Manufac. Part # (Peak Torque/Force, Peak Stall Torque/Force Output)): Elbow Motor – Kollmorgen U9D-E (5.459Nm, 0.487Nm); Forearm Motor – Applimotion (5.08Nm, 1.694Nm); and Linear Motors – Copley Controls TB1102 (9.5N, 3.19N).

Transmission and Actuator Placement A transmission can be used to increase the torques or forces delivered by the device at the expense of speed of operation. Human arm movements are normally in a range of 10–15 Hz, whereas typically DC motors are designed to work at higher speeds. Thus, in haptic device design use of a transmission permits a larger torque output at the human-robot interface, while efficiently utilizing the actuators as the desired speeds of operation are low. Note that detrimental effects due to motor properties, such as cogging are also more pronounced at lower speeds. Furthermore, use of a transmission allows the actuators themselves to be placed closer

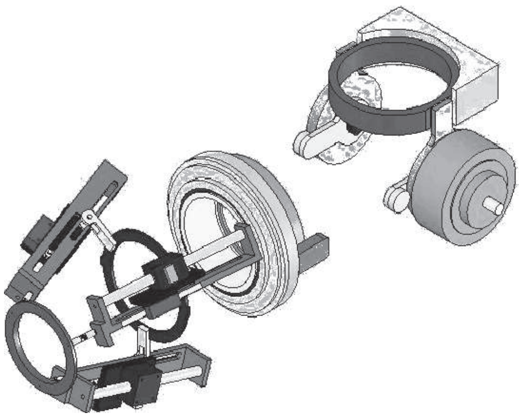

Figure 4. EXPLODED VIEW OF EXOSKELETON ASSEMBLY

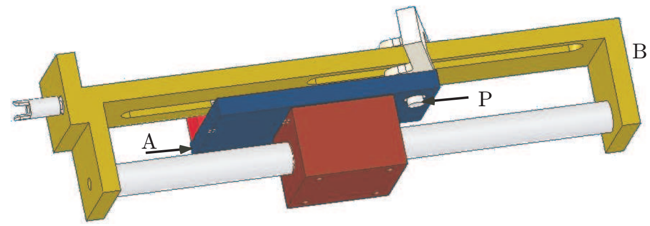

Figure 5. PLATFORM LINK MECHANISM: Link A carries the linear actuator block and rotates about pin P; Link B acts as the prismatic link of the wrist platform. Links A and B are mechanically coupled for synchronous rotation and B can translate with respect to both A and P.

to the base of the robot and reduce rotational inertia.

Use of transmissions, however, is associated with trade-offs like backlash, non-linear dynamics and complex routing. For example, gears introduce backlash into the system, whereas cable and belt drives introduce non-linearities into the system. Additionally, in arm exoskeleton design use of cable or belt drives involves complex routing in order to ensure hindrance free arm operation. Bergamasco et al. used cable drive to power their exoskeleton and reported the routing of cables to be a major part of the design process [4]. The parallel wrist mechanism used in our design can further magnify this problem.

Considering the above mentioned reasons, we use a direct drive mechanism to actuate the robot. This simplifies device design and ensures optimal transparency and performance. The drawbacks include a reduction in the magnitude of forces that can be displayed through the device as well as increased inertia. Frameless electrical actuators were used to keep this increase in inertia to a minimum. As a result of this decision, the current design of the robot cannot compensate for gravitational effects throughout the workspace of the device.

Assembly of the Exoskeleton

Figure 4 shows an exploded view of the robot assembly. The robot uses frameless electrical motors for forearm and wrist joints and is almost entirely made of aluminum. Aluminum has been used for construction over light weight polymers like carbon fiber tubes for several reasons: (a) Aluminum has much higher stiffness than polymers; (b) Polymers, like carbon fiber tubes do not have isotropic strength. They are typically stronger under axial loading than transverse; (c) Being metallic, aluminum components are conducive to the performance of frame less motors; and (d) Due to the use of frameless actuators, the amount of metal required for construction was tremendously reduced and the actuators account for most of the weight of the device. Design of the wrist platform required extra considerations due the to use of electrical actuation. Unlike variable length pneumatic actuators, the electrical actuators used have a fixed total length and hence, the pin joint was replaced with a cylindrical joint with the same axis of rotation. Figure 5 shows the link assembly for the platform. Both links A and B can rotate about the axis of rotation through pin P, whereas link B can also slide over pin P, thus making the cylindrical joint. Bearings have been used in the slots to reduce friction and backlash.

The range of motion of the spherical joint at the movable plate of the platform limits the workspace of platform. Equations developed by Lee and Shah were used to compute the range of rotations required from the spherical joint in order to meet our workspace criteria [24]. It was found that commercially available spherical joints do not suffice to meet the workspace requirements. Hence, the ball and socket joint was replaced by a 4 DOF spherical joint between the top plate of the platform and the corresponding linear joint links. This joint consisted of a a u-joint attached at either end to the link and the moving platform with rotary joints. This adds redundancy to the system and permits larger rotations. For purpose of kinematic analysis however, the redundancy does not affect any of the geometric relations or equations.

Safety and Comfort

During the design of the exoskeleton, precedence was given to the compactness of the design and robot kinematics. A direct drive mechanism was used to avoid backlash and non-linearities associated with transmissions. Owing to these decisions, the robot weighs more than 4 Kilograms. Therefore, the robot was grounded to the wall in order to reduce discomfort to the user.

Hardware stops in conjunction with software limits have been used to ensure user safety and restrict exoskeleton movement within human limitations. Emergency stop switches are

Table 3. WORKSPACE AND TORQUE CAPABILITIES OF EXOSKELETAL JOINTS

Joint	Peak Torque Output	Workspace Capability
Elbow Flexion/Extension	5.46 Nm	Flexion: 90° Extension: 0°
Forearm Supination/Pronation	5.08 Nm	Supination: 90° Pronation: 90°
Wrist Palmar/Dorsal Flexion	$\approx$ 0.4 Nm	Palmar Flexion: 60° Dorsiflexion: $>$ 60°
Wrist Abduction/Adduction	$\approx$ 0.4 Nm	Adduction: 30° Abduction: $>$ 30°

also provided to ensure complete use safety.

DISCUSSION

This paper presents the mechanical design of a haptic arm exoskeleton. The proposed mechanism allows for a compact robot design, centered around the human arm. Table 3 shows the torque and workspace capabilities of the exoskeleton.

It can be easily seen that the exoskeleton design meets the desired workspace specifications, presented in Table 2, for all joints except the elbow joint. The device is capable of allowing for 90° rotation of operator elbow, which is about 30° less than the design specification. It should be noted that the achievable elbow workspace is sufficient for most of the common tasks. The human forearm and wrist capabilities are listed in Table 1. As can be seen, the exoskeleton does not compromise the operators forearm rotation or abduction/adduction of his/her wrist. Almost 90% of wrist workspace can also be reproduced in flexion/extension. Furthermore, this kinematic design allows for a compact robot design, centered around the human arm, in the process increasing wearibility and minimizing the workspace reduction.

In terms of torque reproduction capabilities the peak torque output of the exoskeleton meets the design requirements for the elbow joint and for the rotation of the human forearm. The specifications for torque feedback to the wrist, however could not be met owing to actuator limitations and use of direct drive actuation. Direct drive actuation has been used in order to simplify design and reduce backlash and slip, which helps to verify the functioning of the kinematic design. However, this prevents gravity compensation when the device is in operation, as the continuous output capabilities of the actuators are much less than the corresponding peak output capabilities.

One important feature of the design is the alignment of the axes of the rotation of human joints with the controlled degrees-of-freedom of the exoskeleton of the human arm. The problem of measurement of arm position is thus reduced to the solution of kinematics of the exoskeleton, with no further transformations required as was for the 9DOF masterarm developed at Korea Advanced Institute of Science and Technology (KAIST) [12]. The one to one mapping between robot and human degrees of freedom also facilitates joint based control and force feedback which is not possible for some prior designs, for example [4, 12, 15]. As a training or rehabilitation aid, this permits independent force feedback to human arm joints, thus providing a larger degree of control over the process.

In addition to the above-mentioned advantages due to the proposed mechanism, the device has minimal backlash, low-friction, high backdrivability, high structural stiffness and a singularity free workspace. These features characterize a high quality haptic interface. The absence of singularities in the workspace means that the forward and inverse kinematics of the robot can be solved uniquely at each point, thus making the measurement of arm position and force feedback easier. The use of electrical actuators, which have a high bandwidth, and high-resolution sensors also ensures good performance of the haptic interface.

CONCLUSIONS AND FUTURE WORK

This paper presents the first iteration of the design of a haptic arm exoskeleton for training and rehabilitation. The major limitation of the device is its torque output capability, which can be improved upon with the use of a transmission or counterbalanced links. Despite this limitation, the exoskeleton has several desirable features. The workspace of the robot encompasses almost 90% of the total human forearm workspace, except for the limitation in the flexion of the elbow joint. There exist no singularities in the workspace of the robot. The arm-centered design results in a compact interface that does not compromise natural arm movements. The alignment of human and robot axes permits easy measurement of human arm joint angles alongwith increased control over independent feedback to individual human arm joints. It allows a trainer or therapist to provide customized feedback to individual joints. In addition, the system provides both mechanical as well as software safety features in order to provide a safe training environment for the user.

Future work involves implementation of a force controller capable of providing feedback to various human arm joints independently. Due to the use of direct-drive actuation, it is not possible to compensate for gravity effects with the current design. Use of counterweights or a transmission can be considered for further improvement in performance. This involves a thorough mechanical redesign of the mechanism and a possible increase in device inertia. The exoskeleton interface will be used for implementing and testing shared control methodology for training [21].

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