Performance Enhancement of a Haptic Arm Exoskeleton

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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 space and weight limitations, workspace requirements, and the kinematic constraints placed on the device by the human arm. In this paper, the authors present the redesign of an existing five degree-of-freedom haptic arm exoskeleton. The redesign efforts focus primarily on ensuring smooth operation of the exoskeleton's moving parts to minimize backlash, reducing cost and build time by simplifying the design, and increasing the torque output while continuing to use electric actuators for ease of control. The accompanying computer control system was developed in parallel with the mechanical redesign effort. The newly redesigned exoskeleton presented 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.

Keywords: Haptic I/O, Engineering

1. Introduction

Haptic or force-reflecting interfaces are robotic devices used to display touch or force-related sensory information from a virtual or remote environment to the user (see for example surveys [1-3]). 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, transferring reaction forces to ground. An ungrounded haptic device is attached only to the operator's body, exerting reaction forces on the user at the point(s) of attachment. Typically ungrounded haptic interfaces are good at providing 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]. The workspace of a grounded device is limited by the manipulator's link lengths and joint limits. Often, as in the case of common desktop interfaces like the PHANToM Desktop by Sensable Technologies (workspace: 6.4" W by 4.8" H by 4.8" D) or the Impulse Engine 2000 by Immersion Corporation (workspace: 6" by 6"), the workspace is limited when compared to the workspace of the human arm as determined from the joint ranges of motion for the shoulder, elbow, and wrist. An ungrounded or wearable interface, in comparison, permits greater human movement during haptic interactions. However, 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. Added advantages of haptic simulators include increased repeatability, scalability, safety and control over environmental conditions. 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. This makes a haptic display suitable for a variety of applications like remote operation in hazardous environments, simulators for surgical training [6-8], and rehabilitation research [9-12]. Physical therapy utilizing the resistance offered to a 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]. For these reasons, the authors have developed an arm exoskeleton that can be utilized for such training and rehabilitation applications.

2. Prior Work: Arm Exoskeletons

A force-feedback exoskeleton is a haptic device worn by the user. Arm exoskeletons can 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 grounded, in which case it restricts user mobility. In the mid 1960s and early 1970s, a group of researchers at Cornell University and later at General Electric developed some of the earliest master-slave teleoperation systems, the Handyman and Hardiman [13]. The Hardiman was an anthropomorphic exoskeleton placed inside a larger slave robot, and was used to amplify human power output. Input commands from the user were obtained from both the arms and legs. These early exoskeleton haptic devices were hampered by limitations in actuation, computing, and control systems technology. The reader is encouraged to review [1] for an exhaustive discussion of the early stages of exoskeleton and haptic interface development.

In recent years, improvements in sensing and actuation technologies, control systems, and computing resources have led to the development of many successful haptic interfaces.

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Although there have been a large number of high performance hand controllers, research in design of exoskeletons for other parts of the body is still in an early phase.

The first modern exoskeleton arm/glove was designed and developed at ARTS lab 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 the Korea Institute of Science and Technology (KIST) by Lee et al. [14] addressed the workspace issues associated with the PERCRO exoskeleton. Their device allows for full reproduction of the human arm's workspace when operating the exoskeleton. A revised exoskeleton device from the same group now employs electrical brakes in place of pneumatic actuators for improved bandwidth [15]. An alternate arm exoskeleton developed at KIST addresses the limited wearability issues of previous designs by using parallel mechanisms and pneumatic actuators [16]. The wearable Salford arm addresses some of the issues and limitations of earlier designs [5]. For example, nearly ninety percent of the human arm's workspace can be replicated with their device. Pneumatic muscle actuators (pMAs) were selected to power the robot due to their high power-to-weight ratio. A drawback of this design decision is the highly nonlinear behavior and slow response of the pMA's, presenting additional control challenges.

Several human power amplifier systems, related to exoskeleton haptic devices, have been presented in the literature [17-19]. Human amplifier systems provide force feedback to the operator through a direct coupling between the amplification device and the operator. While there are some overlapping design considerations between human amplification systems and exoskeletons, there are also unique considerations for each. For example, with power-assist systems, the operator directly receives feedback from a natural environment, and the device allows the user greater power output than can be achieved by a human alone. Conversely, a haptic exoskeleton must provide force feedback and simultaneously allow interactions with simulated environments.

Many prior exoskeleton interfaces attempt to optimize one or more of the following characteristics of the haptic system, namely power-to-weight ratio [5, 14, 16], workspace [14], wearability [16] or stability and control bandwidth [4, 20 21]. Individual designs, however, achieve these optimizations at the expense of other useful features, usually workspace [4, 16, 20] or control bandwidth [5, 14, 16].

In this paper, the authors present a newly redesigned and completed arm exoskeleton that combines useful results from prior research and employs novel concepts to produce a high performance, affordable, and simply controlled haptic interface with a workspace comparable to that of the human arm. The new exoskeleton achieves this at the expense of added weight and decreased mobility due to device grounding but remains capable for its intended applications of rehabilitation and training. Figure 1 shows a subject operating the redesigned exoskeleton.

3. METHODS

The MAHI exoskeleton (see Figure 1), named for the Mechatronics and Haptic Interfaces (MAHI) Lab at Rice University, is intended primarily for training and rehabilitation in virtual environments. These applications typically require the use of virtual force fields for guidance [22] or active assistance [23, 24]. The exoskeleton device must therefore allow natural human arm movements, with minimal reduction in workspace of the human arm. Because the device is to be worn, special care must be taken to ensure safety of the wearer. 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 can be implemented through the controller. Additionally, the low accelerations and velocities associated with human movements ensure that the inertia of the device plays a small role in its operation [4, 25]. Therefore, for the first iteration of the MAHI exoskeleton, the kinematic design of the robot was given prime consideration.

In general, haptic exoskeleton design involves various trade-offs: mechanism design choices may limit or affect human motion abilities, sensor and actuator selection is directly related to device weight, force output range, system stability, and cost, and actuator placement and inclusion of transmissions affects the apparent inertia of the device. All of these design decisions are greatly influenced by the intended application for the device. A thorough discussion of specific design considerations for the original exoskeleton and how each was addressed can be found in [26].

The redesign of the MAHI exoskeleton successfully addresses a number of problems which prevented the original exoskeleton from reaching its full potential. The primary problem was limited actuator torque output, but other problems included backlash, friction, a lack of gravity compensation, and a heavy reliance on expensive yet imprecise custom machined components. The challenge was to increase the maximum joint torque output by roughly tenfold while maintaining an electric actuator system, and simplifying the design to minimize backlash and friction in the system.

Table 1 shows the design specifications for both iterations of the MAHI exoskeleton in terms of the torque display capability. The torque capabilities of the new design represent a tenfold or greater improvement over the previous design. The torques achieved by Tsagarakis et al. [5] were used as target specifications for the original design and are also shown in Table

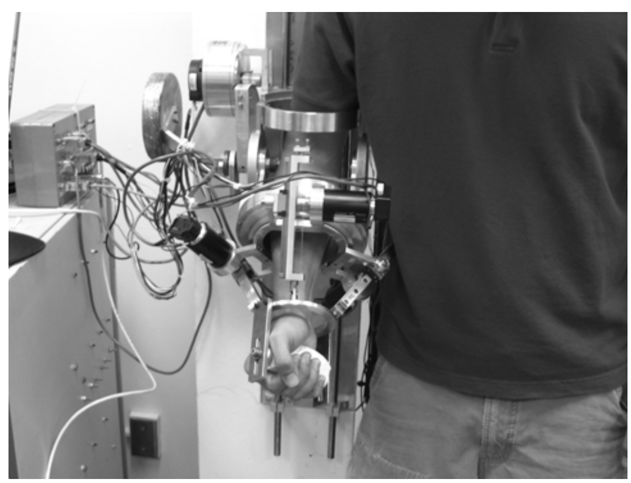


Figure 1. User operating the newly redesigned haptic arm exoskeleton

Table 1. Torque output comparison for original and redesigned exoskeleton

	Human Capability	Salford Arm*	MAHI Arm			
			Original		Redesign	
Joint	Isometric Strength (Ideal Torque Output*)	Torque Specification Benchmark	Actual Torque Output	% of Ideal	Actual Torque Output	% of Ideal
Elbow flexion/ extension	72.5 Nm	6 Nm	5.46 Nm	8%	55 Nm	76%
Forearm supination/ pronation	9.1 Nm	5 Nm	5.08 Nm	64%	5.08 Nm	64%
Wrist palmar/ dorsal flexion	19.8 Nm	4 Nm	0.4 Nm	2%	5.26 Nm	26.6%
Wrist abduction/ adduction	20.8 Nm	4 Nm	0.4 Nm	2%	5.26 Nm	25.3%

*Source: Tsagarakis *et al.* [5]

1. Tsagarakis et al. employ pneumatic muscle actuators with a tendon-based transmission for their exoskeleton design. This allows their exoskeleton to achieve high torque output and a larger workspace as compared to prior arm exoskeleton systems. The disadvantage of using pneumatic actuation is the low bandwidth of the actuators and requirement of delicate control due to their nonlinear behavior. Because the MAHI exoskeleton uses electric actuators, with lower power-to-volume and power-to-weight ratios than pneumatic actuators but with superior control characteristics, the authors felt that the torque requirements of Tsagarakis served as an appropriate benchmark. However, during the redesign effort, the utilization of capstan transmissions enabled the authors to exceed those values and achieve near human isometric strength capabilities. Although the new torque output levels do not reach the maximum output torques of the human arm due to practical size limitations of the actuators and transmissions, they exceed the design benchmarks, and improve upon the previous design by nearly tenfold.

4. Results and Discussion

The basic kinematic structure of the five degree-of-freedom (DOF) MAHI exoskeleton is depicted in Figure 2. The exoskeleton is comprised of a revolute joint at the elbow, a revolute joint for forearm rotation, and a 3-RPS (revolute-prismatic-spherical) serial-in-parallel wrist. The new exoskeleton design maintains the basic kinematic structure and grounded nature of the original design but makes a number of other significant design changes based on the original design's deficiencies. These issues and their solutions are detailed in the following subsections.

4.1. Joint torque output

As shown in Table 1, the original MAHI exoskeleton fell far short of the ideal torque output for several joints, severely limiting the performance of the system. The following sections will separately address the torque output limitations of the 3-RPS wrist platform and the elbow joint of the original design, and how those limitations were addressed in the redesign. The forearm joint (pronation-supination) was not changed from the original design (see [26] for details) since, although it did not meet the ideal specifications listed in Table 1, the joint torque was comparable to that specified as the desired torque output.

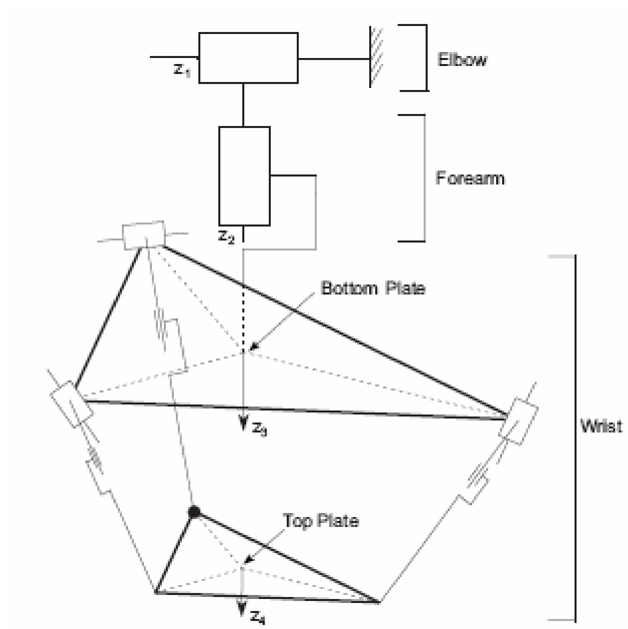
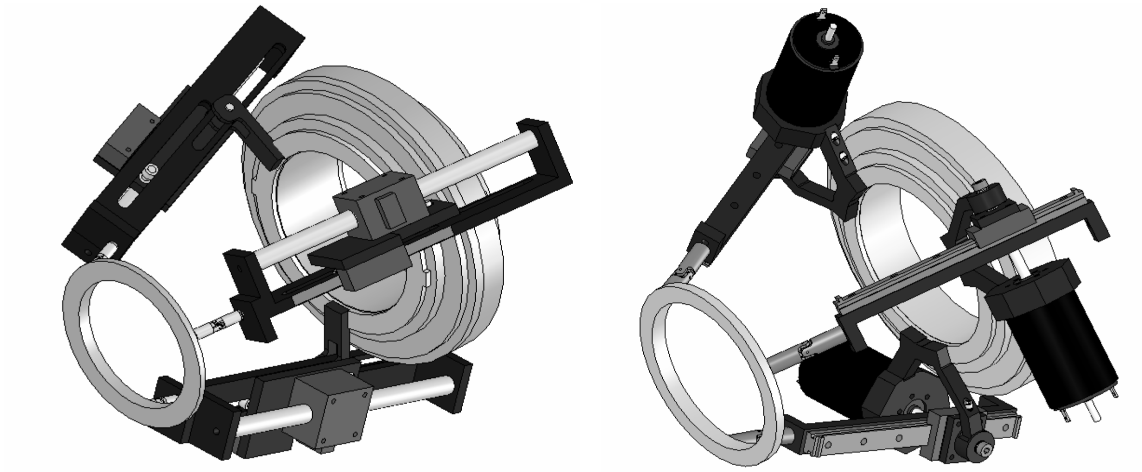


Figure 2. The MAHI exoskeleton mechanism: Revolute joints constitute the elbow and forearm joints, while a 3-RPS platform is used as the wrist of the robot.

4.1.1. 3-RPS Wrist. The actuators in use on the original exoskeleton 3-RPS platform were Copley Motion TT Micro



(a) (b)

Figure 3. The MAHI exoskeleton 3-RPS wrist design. (a) Original version employing linear actuators (b) Redesign employing Maxon DC motors with capstan transmission

model 1102. Chosen for their small size, these linear actuators were only capable of producing approximately 2% of the desired torque output at the wrist. After determining that changing brands, models, or size of the linear actuators would not significantly improve force output, and since design of a transmission mechanism was difficult to incorporate in the existing assembly, the decision was made to switch to high torque rotary electric motors and a cable-driven (capstan) mechanism. The larger Maxon RE40 was chosen for its precision and high torque output. With the capstan transmission that, by design, is backdriveable and free of backlash, the Maxon motor and transmission assembly within the 3-RPS platform is able to provide approximately 25% of the desired torque output for the wrist. Although still below the desired torque output, this represents about a thirteen-fold improvement in torque output over the original design, bringing the joint well within the useful range for training and rehabilitation applications. Removing the actuators from the moving parts in the wrist also reduces the inertia compared to the old design which placed the linear actuator's heavy iron pushrods on each slider. Both the original and new wrist designs are shown in Figure 3. The range of motion of the redesigned wrist for both flexion-extension and abduction/adduction is shown graphically in Figure 4. Ranges of motion for the elbow and forearm are given in [26].

4.1.2. Elbow flexion/extension. The improvements made on the elbow with regard to torque output were similarly dramatic. Previously, the large Kollmorgen U9D-E electric motor on the elbow (see Figure 5) was situated in a direct drive configuration and was incapable of lifting the forearm mechanism against gravity. A transmission system was determined to be the best solution given the available space around the elbow mechanism. Friction, backlash, backdrivability, and size were key considerations in designing the transmission. A large capstan drive with approximately 10:1 transmission ratio was used, allowing backlash-free motion that is fully backdriveable (see Figure 6).

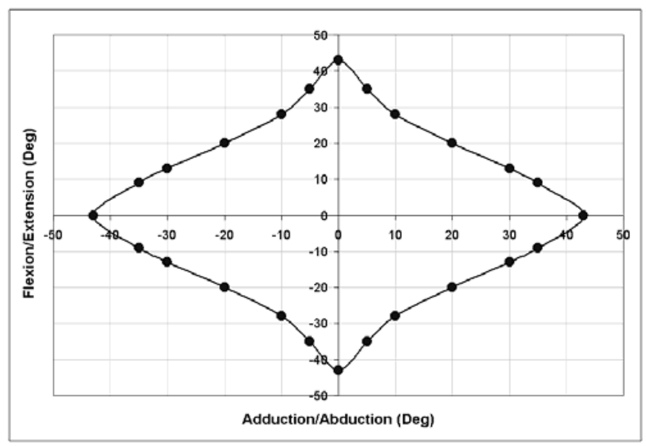


Figure 4. Range of motion for the redesigned 3-RPS wrist of the MAHI exoskeleton

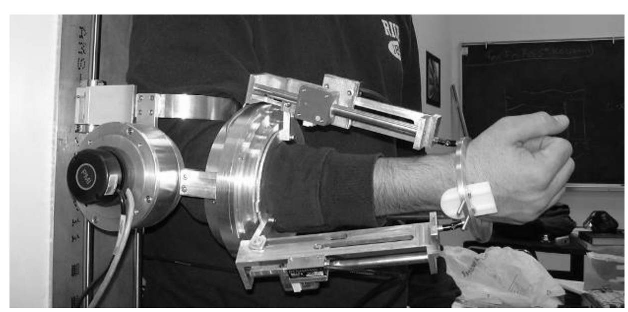


Figure 5. Original MAHI exoskeleton with Kollmorgen motor for direct-drive actuation of the elbow flexion-extension motion.

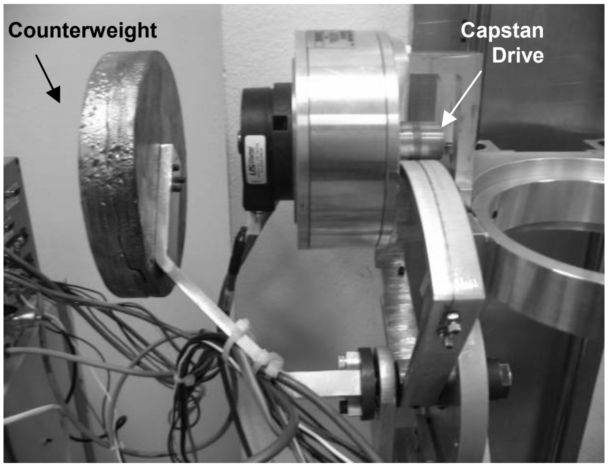


Figure 6. Close-up of elbow joint with capstan drive and counterweight gravity compensation system

To free the elbow actuator from the constant demand of supporting the weight of the forearm system against gravitational forces, a counterweight was incorporated for compensation. The counterweight is directly linked through a moment arm to the elbow motor shaft which supports the forearm assembly, ensuring accurate and continuous gravity compensation. To support the added weight on the elbow mounting shaft and to reduce friction, the shaft now rotates on two large ball bearings in parallel along the axis of rotation. Although such a counterweight gravity compensation system introduces inertia into the system, once freed from the gravitational load of the forearm mechanism, the elbow actuator becomes capable of managing this increased inertia while providing better performance than if it was required to actively support the forearm at all times.

4.2. Friction and backlash

Due to the complex nature of haptic arm exoskeleton design, described in [26], common mechanical effects such as friction and backlash represent significant design challenges. Particularly in the wrist mechanism, the original MAHI exoskeleton suffered from both problems to a significant degree. As a result, there was visibly noticeable play in the joints, occasional binding due to misalignment of the linear actuator and encoder assembly, loose tolerances in custom-machined parts, and friction between sliding components. Specific sources of poor performance in the wrist were the linear actuator and encoder assembly mechanisms, the universal-joints, and the mounting brackets for the linear assembly mechanisms. These components were eliminated or replaced and their accompanying problems solved by shifting to a design centered on precision manufactured components, rigid materials where called for, and an overall reduced number of components in the assembly. It should be noted that many of the initial design deficiencies were resolved by moving from the linear actuator and encoder assembly to the Maxon motor with capstan drive assembly. The result is a mechanical system with smooth and rigid action. The use of off-the-shelf components also reduced build time and cost of the new exoskeleton.

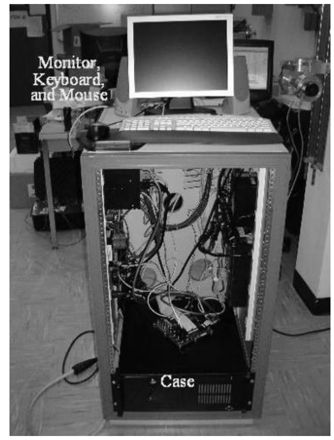


Figure 7. Rack-mounted control computer.

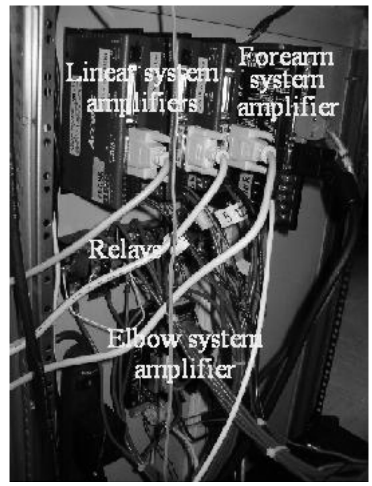


Figure 8. Relays and motor amplifiers for the MAHI exoskeleton (elbow, forearm, and wrist assemblies).

4.3. Computer control platform

The original MAHI exoskeleton design focused only on mechanical hardware. Therefore, as part of the redesign effort, the computational control platform was developed. or computation, a PC with a 3.2GHz Pentium 4 chip and 2GB of RAM was built. To free up processor time, a 128MB graphics card (AGP) was selected. Finally, a 400W power supply and 5 PCI slots are available. The case is rack mounted, with the rack cabinet outfitted with multiple, separately controllable power strips (see Figure 7).

The mobile cabinet was chosen to house and organize the large amount of external equipment needed to operate the robot including motor amplifiers and DC power supplies. Also included is a system of relays between the power supplies and the amplifiers. These systems are shown in Figures 8 and 9, and specifications are listed in Table 2. Note that despite the change from the linear actuators to the Maxon motors for the wrist platform, there was no need to change the power supply or amplifier components, therefore the original systems described in [26] were used.

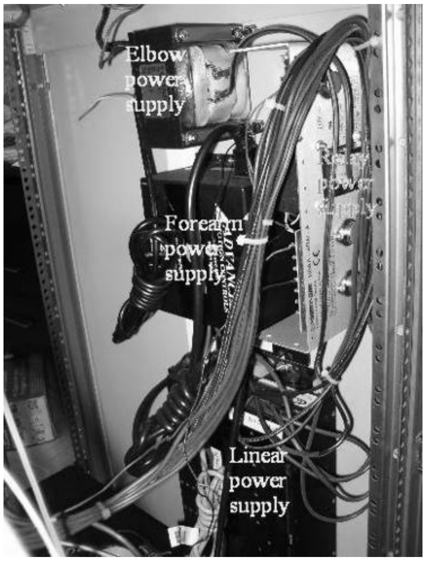


Figure 9. Relays and motor amplifiers for the MAHI exoskeleton (elbow, forearm, and wrist assemblies).

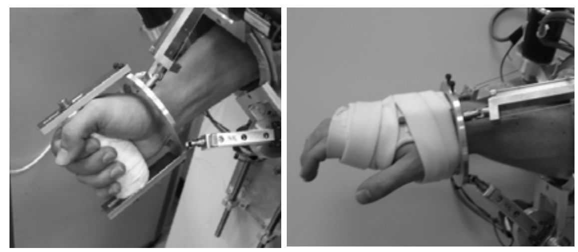
Table 2. Power supply and amplifier specifications

Elbow motor:
Kollmorgen
Power supply: T-48-8A(Transformer) 48V 8A
Amplifier: KXA/48/8/16/PS/AUX
Peak 16A, continuous 8A
Forearm motor:
Advanced Motion Controls (AMC)
Power supply: PS2X3W24 24V@12A
Amplifier: SE10A8
Peak 10A, continuous 5A
Wrist assembly:
Copley Controls
Power Supply: PST-040-13DP 40V@13A
Amplifier: Accellus ASP055-18
Peak 20A, continuous 6A

The hardware is controlled with Matlab Real Time Workshop from Mathworks, and WinCon from Quanser Consulting. All data acquisition is handled by Quanser's Q8 board, designed specifically for hardware in the loop applications. The Quanser board features 14-bit input, simultaneous sampling of A/D and encoder inputs, and extensive input/output options (8 each of A/D, D/A, encoder and 32 DIO).

4.4. Human interface

The original MAHI design lacked robust attachment mechanisms for the wearer's arm. Although a minor design challenge compared to the design of the exoskeleton itself, this issue is of great significance as it is the only part of the exoskeleton with which most users will directly interact. As an additional consideration, because the MAHI exoskeleton is intended for rehabilitation use, it must be accommodating to operators who lack physical strength in their hands, arms, or both. To address these issues, the exoskeleton has two interchangeable accommodations for the hand and a Velcro strap for retaining the bicep and keeping the elbow in alignment. The first hand accommodation is a basic ergonomic, rigid grip suitable for demonstrations and training applications for users will full hand strength. The second is a molded splint that fits tightly around the palm. Two aluminum plates are attached with Velcro to this splint and they are in turn held in place with four long screws that run through the wrist ring allowing a rigid yet comfortable connection. Velcro is then wrapped tightly around the whole assembly to hold the hand in place and to keep the splint well attached to the aluminum support plates. The result is a rigid, reasonably comfortable structure that requires no hand strength to use. These attachments are shown in Figure 10.



(a) (b)

Figure 10. Attachment options for wearer's wrist. (a) grip design, and (b) splint design

5. Conclusions

This paper presents the second iteration of the MAHI arm exoskeleton for rehabilitation and training. In this design, the robot has maintained its large and singularity-free workspace while featuring dramatic improvements in performance in terms of joint torque output. While heavier and less compact than the original design, the torque output of the exoskeleton exceeds that of the selected benchmark and approached human isometric capabilities. Other improvements include the reduction of friction, backlash, and binding that limited the capabilities of the original design. The MAHI exoskeleton is now capable of high fidelity display of haptic virtual environments. Implementation of high-torque electric actuators and capstan drives in combination with gravity compensation has produced a system with powerful capabilities and straightforward control. By incorporating fewer custom machined components in the design and relying more on readily available precision manufactured components, the cost and build times were reduced. An effective computer control platform was developed, and accommodations for the human operator were built. Future work will address implementation of virtual environments and haptic feedback for assistance in both training and rehabilitation of arm movements.

6. Acknowledgements

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