An intrinsically safe mechanism for physically coupling humans with robots

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***Abstract*—Robots are increasingly used in tasks that include physical interaction with humans. Examples can be found in the area of rehabilitation robotics, power augmentation robots, as well as assistive and orthotic devices. However, current methods of physically coupling humans with robots fail to provide intrinsic safety, adaptation and efficiency, which limit the application of wearable robotics only to laboratory and controlled environments. In this paper we present the design and verification of a novel mechanism for physically coupling humans and robots. The device is intrinsically safe, since it is based on passive, non-electric features that are not prone to malfunctions. The device is capable of transmitting forces and torques in all directions between the human user and the robot. Moreover, its re-configurable nature allows for easy and consistent adjustment of the decoupling force. The latter makes the mechanism applicable to a wide range of human-robot coupling applications, ranging from low-force rehabilitation-therapy scenarios to high-force augmentation cases.**

I. Introduction

Robots are increasingly used in tasks that include physical interaction with humans. Examples can be found in the area of rehabilitation robotics and power augmentation robots, as well as assistive and orthotic devices. The physical coupling of the robot mechanism and the human body is of paramount importance because it can drastically affect the efficiency, safety and overall acceptance of the device by the human user. Whether the user is a soldier that desires power augmentation from a robotic armature, or a mobility impaired person that requests assistance from a robot the moves the impaired limb, the way the robot is coupled with the biological limb is one of the most important factors that decides the overall system efficacy.

A human-robot coupling mechanism should meet a long list of requirements. First of all, the human user should be able to easily disengage from the robot in the event of an emergency. Moreover, the coupling should not restrict the human degrees of freedom, and should allow the transfer of forces and torques to the robot body in all directions. Furthermore, the coupling should be adaptive to the user's physical characteristics or to different application requirements. In the case of the upper limb, the coupling should not occupy the human hand, and it should allow seamless interaction of the arm/hand with the environment. Finally, the setup time should be as little as possible.

The coupling mechanisms that have been proposed so far attempt to meet some of the aforementioned requirements, but never all of them simultaneously. Most importantly, nearly none of the current coupling systems offers the user the option to rapidly decouple from the device in the event of an emergency or apparatus failure, whether mechanical or software based. Instead, user safety is entirely reliant upon software and mechanical safety functions such as programmed joint limits, mechanical stops, external emergency buttons, etc, as demonstrated in [1]. While these are features that should always be included as redundant user safety functions, all are reliant on inputs external to the user; Nearly none are at the point of interface itself, giving the user an intuitive, immediate, and complete disengagement from the entire apparatus and coupling system. Instead, for example, the user or observer must notice malfunction and activate an emergency stop. Since malfunction is by nature unexpected and unpredictable, the solution of having safety features external to the user is not always effective.

The HAL upper body exoskeleton is designed for both healthy and impaired users [2]. Recognizing the difficulty of sliding an arm through a closed circle (straps, flexible metal ring, etc) for a user with impaired limb control, HAL uses an open semicircle that is mechanically closed by driving a concentric spur gear to complete the circle once the arm is inserted, as detailed in [3]. This means that not only can the user not disengage from the robot in the event of an emergency, but cannot undo the mechanism coupling him to the device, as it is controlled by that same device, which may be malfunctioning. Furthermore the rigid, closed nature of the coupling prohibits users with different physical arm characteristics, i.e. arm circumference. It is therefore difficult to adapt the coupling system to the individual user, requiring a full fabrication of different size couplings or the addition of inserts.

There are many devices used for motor rehabilitation that use non-rigid straps (e.g. Velcro® straps). Examples can be found in the LOPES system [4], the Lokomat [5], the Shoulder Assist Exoskeleton [6] and the HAL lower body assistive exoskeleton [2]. Moreover, rigid and semi-rigid connection points (vests or metal boot-type snaps) can be found in the BLEEX and HULC devices [7]. While this allows the straps to easily adjust for user size, it still prevents the user from immediately decoupling in the event of an emergency. Furthermore this allows for unwanted movement of the human limb with regard to the coupling and robot in several directions, and distorts the transmission of forces and torques, as shown by [8].

In addition to using Velcro® or fabric type straps and sleeves, and their associated limitations, there are devices that require the user to grasp an end-effector or handle with their hand. Examples can be found in the MIT Manus [9], the augmentation exoskeletons XOS 1 and 2 by Raytheon/Sarcos [10], and the 7 degrees-of-freedom (DoFs) exoskeleton presented in [11]. In several cases this eliminates one or both of the DoFs facilitated by the human wrist. Furthermore, as many of the intended users are impaired by stroke, spinal injury, etc, grasping the handle can be a slow, intensive, and difficult process for both subject and therapist. Perhaps most importantly, this limitation prevents the user from using the hand to interact with the environment, often a critical component of application involving human-robot interaction, whether rehabilitative or augmentative.

Perhaps the solution that comes the closest to meeting all of the criteria simultaneously is the magnetic clutch discussed in [12]. This coupling device uses a magnetic clutch, somewhat similar to the device we present below, to couple the human and robot. The magnetic clutch allows the full transmission of forces and torques from human to robot, and in the case of an emergency, allows the user to immediately decouple by disengaging the magnets. While this is similar to the design presented below, it still does not incorporate an important element: it is not hands-free. Rather than the user grabbing a handle as in the XOS above, the user fits fingers through the coupling, retaining some amount of finger DoFs However, it still occupies the hand and restricts some of its DoFs, resulting in the same issues as the other hand-occupying devices.

Having examined the current state of existing coupling systems, this paper presents the design and experimental evaluation of a novel human-robot coupling system to simultaneously overcome all of these limitations. The coupling we developed is capable of transferring forces and torques from the human to the robot in all directions, allows the hands of the user completely free, is passively and intrinsically safe, and it allows the users to immediately disengage from the robot. Moreover the coupling can accommodate a wide range of users with different body characteristics, it can be used across different body areas (upper and lower limbs), and is adaptive to different operating conditions.

II. Methods

A. Requirements

To overcome the various limitations inherent in current coupling systems as discussed above, we set several driving design requirements for the new coupling system:

1) Safety feature: The coupling must have a safety feature that allows the user to decouple at the point of contact. This function must be both immediate and intuitive, to allow subjects and users with little or no training to maintain full safety. It must be entirely hardware based with no moving or electronic parts to eliminate potential sources of failure due to power loss, etc.

2) Hands-free operation, adaptation, and versatility: The coupling must allow the user free use of the hands. Moreover, the coupling should be capable of adapting to the user, robot, and application. This means it should adapt to the user's physical characteristics (arm or leg size, level of impairment, etc), to the device's interface characteristics (end-effector mounting configuration, screw hole dimensions, etc) so as to be implemented or retrofitted to any device, and to the application, i.e. capable of changing decoupling parameters to suit different applications.

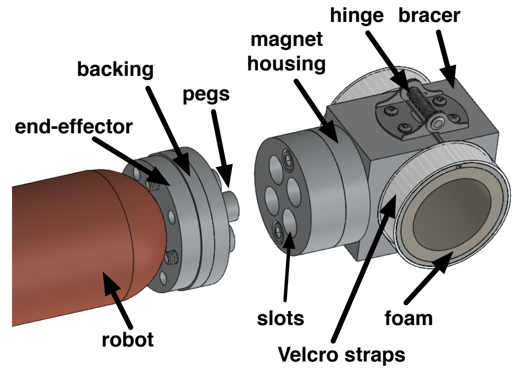

Fig. 1. Coupling components at the human side (right) and the robot side (left).

3) Retain DoFs and force/torque transmission: The coupling should allow the user and device to retain all inherent DoFs not already limited by robot or user operational characteristics. This is important because many possible solutions allowing the user to decouple at the point of interface might prevent the user from moving his or her arm in a certain way or prevent the transmission of force between robot and human along a certain axis, etc.

4) Short preparation/setup time: The user must be able to don and doff the coupling system very quickly to facilitate use and limit energy and time expenditure.

5) Comfortability: The user must be able to wear and operate the coupling system and associated device for extended periods of time.

6) Durability: The coupling must easily endure the stimuli of the intended range of applications.

7) Cost: The coupling must be inexpensive to fabricate and implement so as to facilitate use with existing and future devices.

By designing a coupling that meets these requirements, we create a system that drastically improves upon and is potentially useful to existing and future systems in rehabilitation and wearable robotics.

B. Design

The coupling components are grouped into two sets: the human side, including bracer, magnet housing and slots, and the robot side, with pegs and backing, as depicted in Fig. 1. The user places his limb into the open, hinged, and padded cylinder that makes up the bracer and then uses the Velcro® straps to close and secure it. The pegs and backing are secured to the robot end-effector (in this case with screws, but this can be changed based on the end-effector mounting options). This results in the human wearing one part of the coupling, ending in the slots, and another part attached to the robot, ending in the pegs, as in Fig. 2.

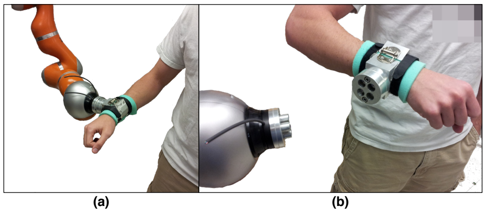

Fig. 2. a) Human-robot coupled configuration. b) Uncoupled configuration.

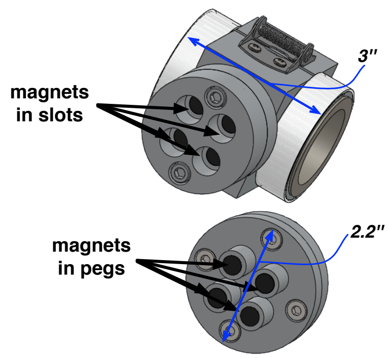

Fig. 3. Opposing magnets in the human side (slots) and the robot side (pegs).

To couple, the user simply brings his limb to the robot end-effector, joining the pegs and slots, as in Fig. 2. At the tip of each peg and the bottom of each slot are magnets, secured via a lip in each housing, as in Fig. 3. When brought together these magnets, which are free to both rotate and move axially within their housings, mate with the magnet of the opposing side, coupling the human to the robot. To decouple, the user simply pulls his arm away from the device in a direction normal to the plane of the magnet faces. When the force the user exerts surpasses the attractive force between the magnets, the human immediately decouples from the robot. In this way, the coupling function is binary, either decoupled or coupled, with no movement or partial disengagement between the two states.

The material of the coupling is aluminum, which is non-magnetic so that it doesn't affect the system performance. Moreover, the magnets used are disc magnets of diameter 3/8 in and thickness of 1/4 in and 3/8 in respectively ((SD64-OUT, D62-N52, K&J Magnetics).

In implementing this design, the coupling meets all requirements that we have previously defined:

1) Intrinsic safety: The coupling provides the user with a safety function in case of emergency, in which a user's intuitive response to malfunction (pulling away from the potentially harmful device) results in immediate decoupling and avoidance of harm and requires little to no training. By using permanent magnets the safety function requires no moving parts, electronics or software, thereby avoiding potential sources of failure.

2) Hands-free and versatility: The bracer, shown on the wrist in Fig. 1 and 2, can also be attached to the user's ankle, calf, or other parts of the upper or lower limb, ensuring the user's hand or foot remains free as it is not necessary for coupling.

3) Adaptive and fully adjustable behavior: The hinged, padded nature of the bracer ensures that the coupling fits all sizes of users and both upper and lower limbs. Because the flange between the pegs and device is modular and dedicated to attaching the coupling to the device, it can easily be customized to fit nearly any device. Most importantly, the coupling can be adapted to any application. This is because each of the four pegs and slots has a housing, accessible due to the modular, screw-braced design, capable of containing several stacked magnets. The user can vary the size/strength of the magnets used, which pegs they are in, and how many are successively stacked in each peg. By doing so, we can control and adjust the attractive force between the two sides of mated magnets, and therefore force needed to decouple. The human uses this control to adapt the coupling to the expected application forces. For example, in a rehabilitation application, the impaired patient might only be capable of exerting low forces, so the therapist uses only a few magnets resulting in a low decoupling force (or threshold). In another case, the same coupling system, by inserting more magnets, can be used in an augmentative exoskeleton application at high decoupling force. The theoretical range of attainable coupling force is from 35 to 160 N, but changing the magnet housing dimensions can easily and widely vary either of these criteria. The resolution of attainable forces is nearly infinite. This is for two reasons: supplier's range of rare earth magnets includes a very fine resolution of magnetic strength within the sizes of magnets usable in the coupling, and because the attractive force a magnet contributes to the coupling is inversely proportional to how far back in the housing it is stacked, allowing the user to choose the exact amount of force contributed [13].

4) Force-torque transfer in all directions: While isolated pairs of magnets do not prevent shear force or rotational torque, the peg-and-slot configuration allows the transmission of shear forces, while having multiple pegs allows the transmission of torques. Thus, the coupling allows transmission of forces and torques in all dimensions, and does not limit any DoFs of either the human or robot.

5) Durability: The aluminum body ensures the coupling can easily endure any forces and torques within the expected range of application parameters while maintaining a light weight.

6) Comfort: This light profile, in combination with the use of memory foam as padding, and the ability to disengage and reengage the coupling at any time, ensures the user is comfortable for long periods of operation.

7) Short preparation/setup time: The Velcro® strap and hinge allow a healthy user or therapist-patient tandem to don or doff the coupling system in less than 15 seconds, while maintaining comfort and preventing the coupling from rotating with respect to the human arm.

8) Cost: Finally, the materials cost of the entire coupling system was under \$50, allowing its inclusion in current or future robot-human devices.

Having theoretically met the design requirements, we conducted several experiments to confirm the coupling's performance.

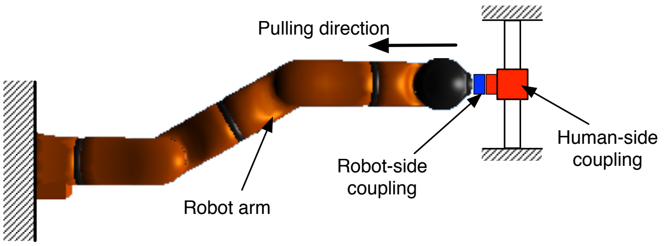

Fig. 4. Experimental setup where the robot arm disengages from the human-side of the coupling mechanism. The coupling is mounted on a solid cylinder. The robot pulling direction is perpendicular to the mounting cylinder.

C. Experimental Verification

The aim of the experiment was to confirm the performance of the mechanism's primary functionality, the magnetic coupling. To this end, the human side of the coupling was fixed to an immobile support via the normal user-fitting procedure, i.e. bracer and Velcro® straps. The robot side of the coupling was affixed to the end-effector of a 7 DoFs anthropomorphic robot arm (LWR4+, KUKA Inc). The experimental setup is shown in Fig. 4. For each trial, the robot and support began fully coupled. The robot then pulled away from the support in a direction normal to the coupling face with increasing force until decoupling, i.e. the surpassing of the mated magnets' mutually attractive force, occurred. The force exerted by the robot began at zero and increased by 0.125 N/ms until decoupling, or until 250 N was reached and the trial aborted. The robot was controlled in Cartesian impedance mode, so that it develops the force progressively, as well as stops smoothly after the decoupling has occurred. Eight (8) trials were done for each configuration.

In order to test the adaptive characteristic of the coupling in terms of the required disengagement force, six (6) different configurations of the magnets were used. Each configuration of magnets had a different theoretical maximum force- the force needed to decouple, controlled as explained in the Design section. The configurations tested include different numbers of magnets put in parallel and/or in series (stacking), as shown in Fig. 5. The theoretical magnet-to-magnet pull forces of the magnets used were computed using information from the manufacturing company found in [14]. Two kinds of magnets were used: 3/8in diameter step-out magnets (SD64-OUT, K&J Magnetics) were used exclusively at the point of contact for a contributing force of 34.7 N each and 3/8in diameter straight magnets (D62-N52, K&J Magnetics), were used exclusively stacked behind the step-out magnets for a contributing force of 2.2 N each, were combined to create the six magnet configurations. These configurations, amount of each magnet used, and total theoretical decoupling force are listed in Table I. Finally, for the duration of each trial, the robot end-effector force was measured and recorded at a sampling rate of 500 Hz.

III. Results

The recorded force for each trial consistently followed the designed, expected pattern. It rose as the robot exerted force, until exceeding the attractive magnetic force and decoupling, at which point measured magnetic force rapidly returned to zero. Each successive configuration, with consecutively greater

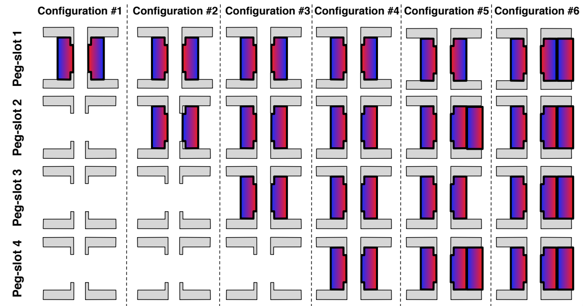

Fig. 5. Magnets configurations tested.

TABLE I. Magnets configurations tested

Configuration #	# step-out magnets	# straight magnets	Theoretical decoupling force (N)
1	1	0	34.7
2	2	0	69.4
3	3	0	104.1
4	4	0	138.8
5	4	2	143.2
6	4	4	147.6

theoretical decoupling force, showed a greater maximum force exerted by the robot just before decoupling occurs. This rise of force to decoupling, as well as comparison of configurations, can be seen in Fig. 6. The maximum force of each trial was found and recorded, then grouped by configuration. A box plot of these maximum forces showing all configurations, with means and standard deviations of maximum force, as compared to the theoretical force for each configuration, is shown in Fig. 7. Finally, Table II lists this data, as well as the mean of the recorded force for each configuration as a percentage of the theoretical (expected) decoupling force for that configuration.

The results verify that the magnetic coupling system works properly, as expected. The decoupling was very consistent; for a given configuration, the measured force needed to decouple varied very little between trials (see standard deviation (std) in Table II). Not only is the coupling mechanism consistent within a single set of parameters (i.e. magnet configuration), it also scales properly as a function of its intended independent variable- the theoretical decoupling force, achieved via magnetic configuration.

As can be seen by the percentage of the theoretical decoupling force in Table II, the measured force needed to decouple is linearly related, and correlates very well, with the expected (theoretical) decoupling force; the measured force is very consistently near 80% of the theoretical, with the exception of configuration 2, which is still 72%. A possible source of this *systematic* error between the experimental and the theoretical values of the decoupling force, is slight misalignment of the opposing magnets that would result to a reduction of the attractive force. In fact, a 30° misalignment can reduce the attractive force up to 20%. Moreover, the difference in force can be due to magnet specifications' errors, as well as non-full contact between magnets due to slight misalignment. However, the experimental procedures demonstrate the repeatability and the consistency of the coupling performance, as well as the adjustable characteristics of the device in terms of the decoupling force.

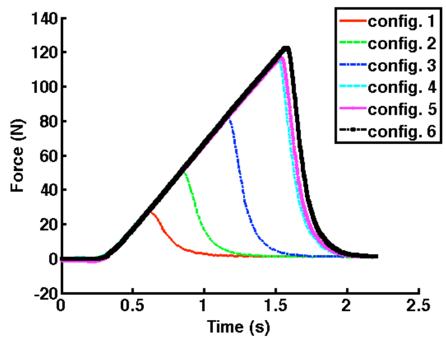

Fig. 6. Force applied by the robot for decoupling across the six tested configurations. The peak force for each configuration corresponds to the force for decoupling.

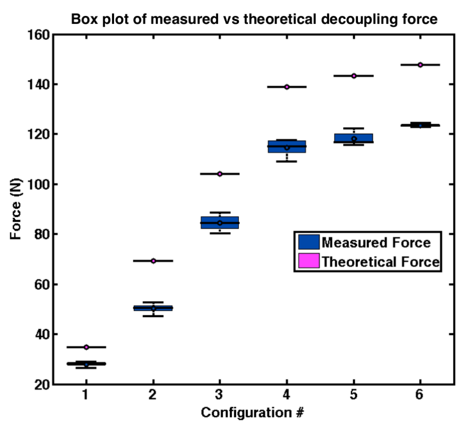

Fig. 7. Measured versus theoretical decoupling force across configurations, using 8 trials per configuration.

IV. Conclusions

In this paper we present the design and verification of a novel mechanism for physically coupling humans and robots. The device is intrinsically safe, since it is based on passive, non-electric features that are not prone to malfunctions. The device is capable of transmitting forces and torques in all directions between the human user and the robot. Moreover, its magnetic and configurable nature allows for easy and consistent adjustment of the decoupling force. Based on the availability of the magnets and their range of developed forces, we can assume that the resolution of the decoupling force adjustment is as low as 0.1N [14]. This makes the mechanism usable to a wide range of human-robot coupling applications, ranging from low-force rehabilitation-therapy scenarios to high-force augmentation cases. Some of the unique features compared to current solutions include the following: the device doesn't limit or impede the human limb motion, allows hands-free operation in the case of the upper limb and the decoupling is immediate once desired by the user or the conditions of the application.

The device is already utilized in research projects involving upper limb rehabilitation scenarios, as well as arm exoskeletons for augmentation purposes. In the near future we will further investigate the *systematic* difference we noticed between the expected and measured decoupling force across different magnet configurations. Magnet alignments methods are already under development for the next version of the coupling. Moreover, a considerably larger coupling to be used for the lower limb is currently under development. A provisional patent application (No. M13-025P) was filed to the United States Patent and Trademark Office in October 2012.

TABLE II. Experimental versus theoretical values of decoupling force.

Configuration #	Theoretical Decoupling Force (N)	Measured Decoupling Force (N) [Mean ± std]	Accuracy (%)
1	34.7	28.0±0.8	80.6
2	69.4	50.3±1.7	72.5
3	104.1	84.5±3.0	81.2
4	138.8	114.6±3.0	82.6
5	143.2	118.1±2.4	82.4
6	147.6	123.5±0.6	83.7

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