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Design issues for human-machine platform interface in cable-based parallel manipulators for physiotherapy applications*

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Abstract: We outline problems and potential solutions for feasible human-machine interfaces using cable-based parallel manipulators for physiotherapy applications. From an engineering perspective, we discuss the design constraints related to acceptance by patients and physiotherapist users. To date, most designs have focused on mobile platforms that are designed to be operated as an end-effector connected to human limbs for direct patient interaction. Some specific examples are illustrated from the authors' experience with prototypes available at Laboratory of Robotics and Mechatronics (LARM), Italy.

Key words: Robot design, Robot applications, Cable-based parallel manipulators, Human-machine mechanical interfaces
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1 Introduction

In the last decade, medical applications for parallel manipulators have been identified as key challenges and feasible goals for special service robots. Although engineering solutions and approaches have fostered interesting applications and prototypes, they are still not readily available and applicable for users (e.g., patients and doctors) at a reasonable cost or with user-friendly operability.

Cable-based parallel robots have recently attracted interest for use in these applications, since they can overcome some drawbacks in operation and design that have limited the use of serial chain manipulators and traditional parallel architectures. A cable-based parallel manipulator has the structure of a traditional parallel manipulator, but the actuating links are made of cables whose motors exert pulling forces only (Fig. 1).

There are many efforts concerning system design and operation planning, the solutions are typically considered only from technical viewpoints, although a certain number of medical collaborations have occurred, as reported, for example, in the proceedings of International Conference on Rehabilitation Robotics conferences in 2003, 2005, 2007 and 2009 (ICORR, 2005; 2009). In particular, considerable attention has been directed at rehabilitation systems and specifically physiotherapy applications with the aim of developing systems that can solve specific medical problems facilitate rehabilitation, including helping patients achieve autonomy in daily exercising or other rehabilitative therapy.

It is well known that repeated limb movements help patients to regain some of their lost functions and strengthen others. Repetitive task robots are well suited for this purpose, since they can train patients for long durations and with a suitable precision, potentially yielding better results than human trainers. Moreover, robotic systems coupled with virtual reality simulators may enhance conventional physical therapy methods, since they can record all the required information on the state of the patient in real time. The data may include total exercise time, speed of movement, peak and average velocities, and

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mechanical work, providing an objective measure of the progress and outcomes of therapy.

Cable robots are capable of carrying high loads, and have a large range of motion with rapid deployment, compactness and easy reconfiguration. Not surprisingly, several cable robots have been proposed for rehabilitation. Illustrative, well-known examples include MACARM (Multi-axial Cartesian-based Arm Rehabilitation Machine) (Mayhew *et al.*, 2005), STRING-MAN (Surdilovic *et al.*, 2007) (Fig. 2), and Maribot (Rosati *et al.*, 2007) (Fig. 3). More experimental examples remain in development at the laboratory level. Information on these is available in conference proceedings such as those from ICORR conferences, and these examples are not dealt with here.

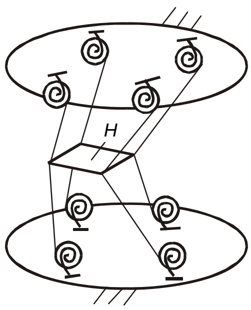


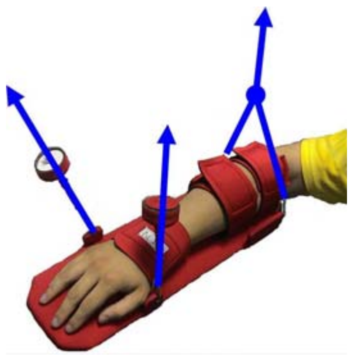
Fig. 1 A general design of cable-based parallel manipulator with *H* end-point

(a) (b)

Fig. 2 Patient interface in STRING-MAN system (Surdilovic *et al.*, 2007). (a) An installation of a human patient; (b) A view of the simulated full system

MariBot is an enhancement of NeReBot (NEuro REhabilitation Robot), which is a cable-suspended device for upper limb rehabilitation of post-stroke patients (Fig. 3). Three nylon wires convert the rotating motion of three DC motors into a 3D trajectory of patient's arm (Fig. 3b). A real-time software program performs both on-line point-by-point acquisition and repetition of the 3D trajectory obtained by interpolating the acquired points.

(a)



(b)

Fig. 3 MariBot (Rosati *et al.*, 2007). (a) A view of the full system; (b) A scheme of the platform for upper arms

Safety and comfort issues for disabled patients are of great importance, since these patients often have limited reflex capabilities and hand-eye coordination. The user-machine interface is an important consideration to ensure security and comfort during a rehabilitation session. Thus, acceptance of the design from both patients and therapists is more likely when the therapist-assisting device being used for guidance/assistance of limb exercises or movements has clear features of comfort and safety (Ceccarelli and Ottaviano, 2008).

In this study, we address the importance of attention to design and operation of the human-machine interface for the end-effector mobile platform in cable-based parallel manipulators as a main issue to achieve application efficiency, comfort, and safety in physiotherapy applications. Problems are introduced with subsequent discussion of a general framework for the provision of solutions to these problems, using specific cases as illustrative examples.

2 Interface problem

The problem for human-machine interfaces in cable-based parallel manipulators lies mainly in the design of a suitable mobile platform and its comfort and safety during operations.

The shape, size, weight, cable-connections, and appearance of the mobile platform can be considered as the main outputs of a design procedure which should take into account not only technical matters, but also user-oriented constraints and goals.

The comfort in the design of the platform is of primary importance. Indeed, intense and long physical therapy requires a certain level of comfort for a patient to continue effectively. Thus, the platform must be shaped with ergonomic features, but these may constrain the location and shape design of cable attachments. The ergonomic design can be specified for limb anatomy, but nevertheless should have adaptability to the specific anatomy of each patient. Thus, some size and shape adjustments should be possible. But when the kinematic performance of the assisting cable device cannot be reformulated accordingly, it is helpful to consider a platform design in which an adjustable and movable limb interface can be installed or connected to the platform.

The size and shape of the platform, together with location and shape of the cable attachments can provide different considerations for the kinematic design of parallel manipulators. Thus, the design can be formulated with those requirements/constraints for the structure of the kinematic chain and mechanical design for the cable attachments.

Comfort issues can also involve psychological responses of the patient, referring to acceptance of interacting with an assisting device whose cable movement is visible and proximate. These cable movements should be very smooth with a path that avoid disturbing the patient. Thus, complex or intersecting cable-crossed figures and vibrating cables should be avoided.

Safety issues add to the burden of the above-mentioned requirements, with a need to identify limit conditions which may be risky for patients or caregivers. Thus, for example, the motion of the movable end-effector platform should be limited to a prescribed area and movements in accordance with both the specific therapy needs and the patient's psychological attitude.

In addition to the specific kinematic and mechanical design of the platform and its cable attachments, the interface for human-machine interaction will require alarm and sensing equipment on the platform to monitor the status and results of platform motion and action relative to the limbs of the user. Those sensors should be installed on the platform, but lead to further constraints in the user-oriented design of the platform.

In addition, braces should be used to properly fix the patient's limb on the platform, and their design and location can significantly influence the platform design in term of size and shape as well as the location of the cable attachments (which should not interfere with brace adjustment). Furthermore, the type of braces used to strap the patient should be designed to avoid excessive pressure on the skin.

In Fig. 4 the interface problem for platform design is summarized, referring to the general terms of platform size and location of cable attachments. Both will determine the topology of the parallel manipulator chains in the sense that attachment location can be constrained by the platform size and shape. In general, the cable attachments can be located to facilitate accommodation of human limbs, but also to permit therapist intervention on the accommodated limb. These aspects can further suggest symmetrical solutions as shown in Fig. 4 with as many cables needed to achieve under actuation to redundant designs.

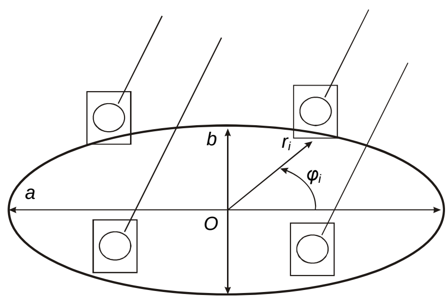


Fig. 4 Design size of an end-effector mobile platform in cable-based parallel manipulators in Fig. 1

r_i and φ_i are polar coordinates of the connecting joints in the platform

A further fundamental problem is the fulfillment of medical protocols that require additional requirements in both design and operation. As the device interacts with the human body, medical applications will require designs which allow for easy cleaning after use, and easy operability. In addition, the material should be selected to avoid any interference (e.g., electromagnetic fields, waste production) with other medical equipment. For summarization, the interface problem for the design of the platform of a cable-based parallel manipulator for physiotherapy applications often requires consideration of technical problems mainly related to the ergonomics and medical protocols, even more than to the constraints and requirements for safety and patient acceptance.

3 Design considerations with operation constraints

Design considerations can be outlined from the previous considerations as they apply to physiotherapy according to Fig. 5.

In this flowchart, in specific blocks, we have indicated several activities that are necessary for successful design in practical applications. Although we have indicated many aspects that are mainly related to operation issues, they can be still considered fundamental at the design level. Thus, there are blocks which indicate aspects for patient attitude and therapy operation with or without supervision of medical operators. Although the proposed procedure can be considered a general approach for design and operation of medical systems, the proposed flowchart has been considered mainly in the specific case of cable-based parallel manipulators for physiotherapy applications. In particular, the design approach has been conceived in three main parts, namely a properly defined design process, considerations for comfort issues, and consideration for safety issues.

The proper design process is based on technical aspects with data inputs, technical computations, medical requirements in terms of system constraints, and checks with respect to system functionality and acceptance by patients and medical operators. Data inputs deal with technical aspects and medical constrains, as discussed in Sections 1 and 2. Technical computations deal with the kinematic design, evaluating its basic performance as related to a specific application, and further deal with the size and operation of the system. Thus, topics such as workspace evaluation, singularity analysis, stiffness response, path planning, and human-machine interactions will be dealt with in numerical simulations and design algorithms. Once the cable-based parallel manipulator

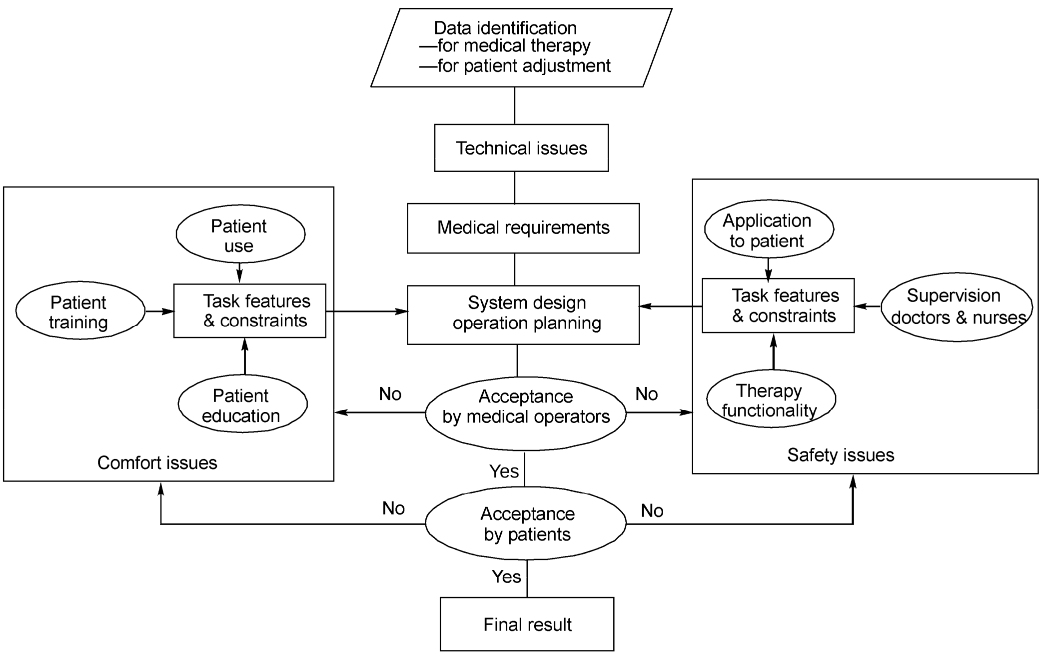


Fig. 5 A flowchart for a design procedure of cable-based parallel manipulators for physiotherapy applications

is defined, its functionality can also be evaluated with an iterative process as it relates to safety and comfort issues. Once a satisfactory solution is identified, final checks can be performed at the design level and with prototype experiences. These checks should be mainly directed to validate the practical feasibility of the design solution and its operation as viewed by medical operators and patient users. This last activity can be indeed the most problematic, since it requires bringing the designed system into medical environments and existing medical protocols.

The design activity for comfort issues is described in Fig. 5 as an identification of task features and constraints as considered from patient viewpoints. The main patient viewpoints are related to the education and training of patients about technology as medical assistance, and more specifically how the cable-based parallel manipulators assist with her/his physiotherapy. In addition, an important aspect in defining comfort issues is the specific utilization of specific cable-based parallel manipulator by patients. Indeed, this design activity can be carried out with the help of patients, but often this can only achieved in final phases of prototype validation.

Similarly, but with a very different approach because of more technical insights, the design activity for safety issues can be aimed at identifying task features and constraints both for design outputs and operation performance in cooperation with medical operators and patients. Human-machine interactions can be considered for safety issues, namely as related to the direct interactions of the assisting device with the assisted patients and with medical operators who can prepare and operate the system both for acting on the patient and for supervising the therapy exercise.

Specific design considerations for cable-based parallel manipulators are outlined in Fig. 5. The aim should be to define a specific design procedure that will include items from technical viewpoints like definition of the structure of the parallel chain, computation of the size and shape of the mobile platform, location and mobility of the cable attachments in the mobile platform, actuator selection and cable tensioning, control algorithm and equipment, evaluation of operation performance, path planning, dynamics response, evaluation of human-machine interactions, monitoring and simulation of motions and actions during therapy.

4 Laboratory experiences at LARM

Experience has developed at the laboratory level mainly from technical viewpoints, with the aim of achieving efficiency in simulated mechanical designs and/or prototypes elaborated upon within the authors' teams. These experiences have motivated us to consider the problem of human-machine interface as a necessary step in developing feasible applications.

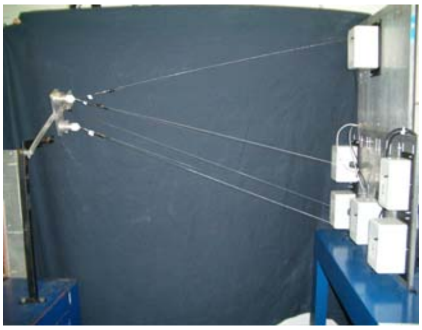
At LARM in Cassino, simulations and designs have been computed in detail and have lead to prototype solutions both in design and operation features (Ceccarelli *et al.*, 2007; Ceccarelli and Ottaviano, 2008). More details are reported in the references from presentations at LARM (2009). In the following sections, those experiences are summarized in terms of issues being discussed here. In particular, in Fig. 6, CATRASYS (Cassino Tracking System) and CALOWI (Cassino Wire Low-cost Parallel Manipulators) are the systems for which we have experience in diagnosis and rehabilitation exercise, respectively.

In Fig. 7, CATRASYS is shown as applied to monitoring human limbs movements (Palmucci *et al.*, 2007; Grande, 2008). Most of the experiments have been carried out for human walking analysis for diagnosis and parameter identifications purposes. The human-machine interface is shown in Fig. 8 as a practical lab solution, and is not considered a proper interface for clinical applications.

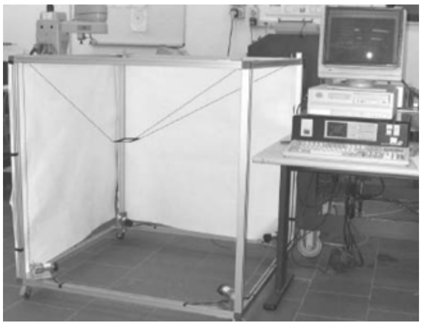
CATRASYS is composed of a mechanical part, an electronics/informatics interface unit, and a software package. In Fig. 6a, the mechanical part consists of a fixed base, the Trilateral Sensing Platform, and a moving platform, the end-effector for CATRASYS. The two platforms are connected by six cables, whose tension is maintained by pulleys and spiral springs fixed on the base and is monitored by suitable force sensor units. The end-effector for CATRASYS in Figs. 6a and 8 is the moving platform operating as a coupling device: it connects the cables of the transducers to the extremity of a movable system. It allows the cables to track the system while it moves. Signals from cables transducers and force sensor units are fed through an amplified connector to the electronic interface unit, which consists of a computer for data analysis. In particular, suitable reference points are used to determine the position and orientation of the moving platform, which is the end-effector for

CATRASYS, whose architecture can be extended up to a 3-2-1 solution.

In Fig. 9, the operation mode is shown with three cables attached to an ankle point to track its position during walking. CATRASYS has been used mainly for diagnosis purposes to identify the limb parameters, motion patterns, and force capability during limb motion, as shown in the example in Fig. 6a.



(a)



(b)

Fig. 6 Designs of cable-based parallel manipulators at LARM in Cassino (Ceccarelli *et al.*, 2007). (a) CATRASYS (Cassino Tracking System); (b) CALOWI (Cassino Wire Low-cost Parallel Manipulators)

Fig. 7 A walking analysis with CATRASYS

Fig. 8 An end-effector interface for CATRASYS on an ankle application at LARM in Cassino (Grande, 2008)

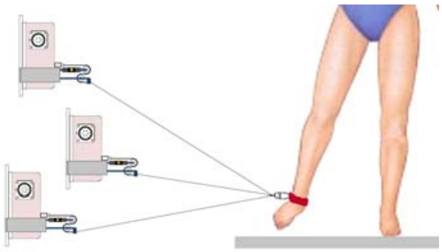


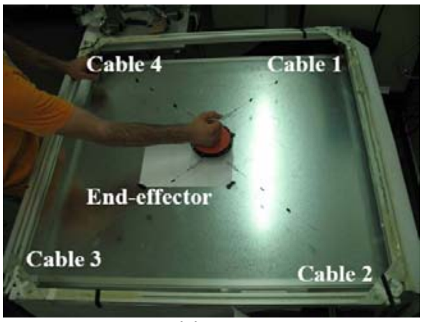
Fig. 9 An operation configuration with CATRASYS at LARM in Cassino (Grande, 2008)

CALOWI is comprised of a mechanical cubic-frame structure, a controller, a PC for programming and monitoring, and a suitable end-effector, as shown in Fig. 6b. The actuation system is comprised of four DC motors, which can extend or retract cables, whose tension is measured with suitable sensor units near the motors. The cubic-frame structure allows one to operate the parallel manipulator for either planar or spatial tasks. In particular, the current CALOWI design operates as fully constrained for planar tasks in upper plane of the frame, and as unconstrained for spatial tasks within the volume of the cubic-frame structure. CALOWI has been used for limb exercises to guide the limb motion patterns and force capability (Fig. 10).

5 Examples

The presented considerations can be applied in the proposed design procedure in collaboration with medical operators and patients to achieve solutions acceptable within medical protocols for rehabilitation.

There is still a great reluctance, however, and indeed difficulty in communication and understanding



(a)

(b)

Fig. 10 Exercises of human limbs with lab interfaces for CALOWI. (a) Guiding arm motion; (b) Imposing leg movement

within the collaboration of engineers and medical operators.

Nevertheless, preliminary developments can be elaborated even at the laboratory level while simultaneously considering the needs expressed by the medical operators, and by enhancing technical solutions from previous experience.

Thus, by looking at solutions from laboratory experiences at LARM in Cassino, it has become possible to elaborate new solutions and enhancements related to the operation of CATRASYS and CALOWI, as illustrative examples of the proposed design procedure. It is noteworthy that the differentiation of the interface platforms for CATRASYS and CALOWI have been determined by the specific applications with users. Thus, the belt interface in Fig. 8 can be easily improved by using a band with a suitable cable attachment, as in the proposed solution in Fig. 11. The band will not only provide for limb comfort with a soft adjustable contact, but also can provide a location for the cable attachment for positioning the monitoring/guiding point. The proposed cable attachment is an adaptation of the mechanical solution that has been designed for CATRASYS, as shown in Fig. 6a. It can be improved upon with a reduction in size and also suitable light mechanical design by using proper materials. The band solution is convenient mainly for comfort issues, but if an accurate positioning of the cable attachment is required, it cannot solve this problem as well. Thus, as a further example, to refer to a point for its axis of articulation rotation, the interface in Fig. 12 can be considered a better solution. The new design consists in a cable attachment on a compact universal joint that is installed on the revolute axis between two rods. The two rods of adjustable length with proper shape can be fixed on the two links joining the knee articulation by means of suitable strap bands. Indeed, more cable attachments can be fixed on the rods to have the desired parallel architecture for the interface platform. Additional cable attachments can provide more degrees of mobility for the monitoring/guiding task.

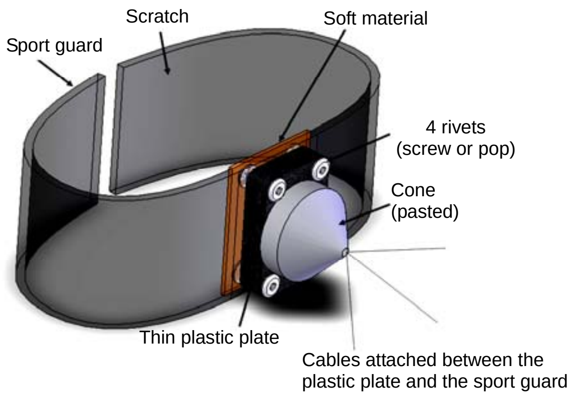


Fig. 11 A platform interface with fixing band and cable attachment

Cable connections can be obtained with suitable mechanical design as shown in Fig. 6a, or even by using universal joints or spherical joints on which a suitable hook connection can be added.

Thus, Fig. 13 shows a solution with 3-2-1 architecture with the possibility of tracking and guiding both limb position and orientation.

Furthermore, the proposed solution in Fig. 13a has been conceived using a commercial sport guard product to satisfy requirements of both a low-cost and user-friendly solution. Using shaped platforms or even products that are familiar to patients can satisfy comfort issues, patient acceptance, and technical needs.

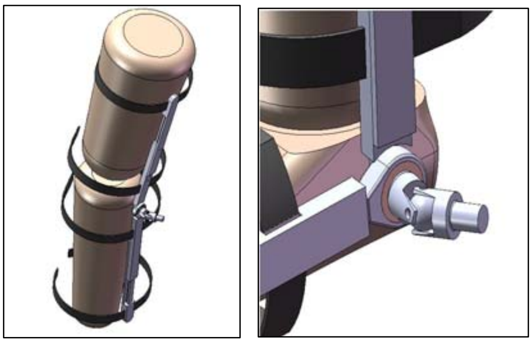
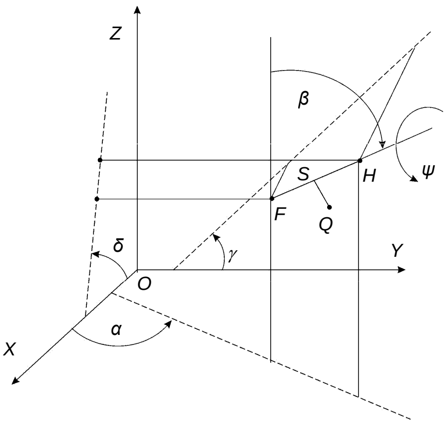


Fig. 12 A design for a new end-effector interface for CATRASYS (Grande, 2008)

(a)

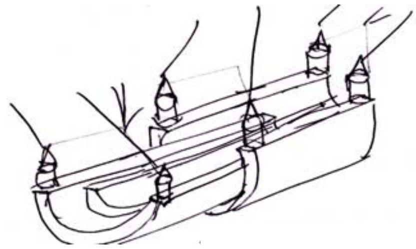


(b)

Fig. 13 A design for 3-2-1 platform interface for leg applications. (a) Prototype solution with sport leg guard; (b) A scheme with three connection points *H*, *F* and *Q* for orientation purposes described by the angles *α*, *β*, *γ*, *δ*, and *ψ*

A more general solution achieved together with a doctor is shown in Fig. 14a, combining previously discussed design considerations with practical features. Two cylindrical shaped parts are connected by a sliding joint for adjusting the size for limb accommodation. Comfort and full adjustment can be obtained with a soft, properly shaped frame. Cable attachments can be located all around the upper aspect of the interface platform and each one can be designed for one or more cable attachments to obtain the chain structure that is more convenient for monitoring/guiding tasks, and for operation functionality.

In particular, a mechanical design can be elaborated as shown in Fig. 14b, addressing technical issues and the above-mentioned requirements for comfort, safety, and psychological acceptance. Thus, the general idea in Fig. 14a is shown in a CAD design in Fig. 14b, where the support is made of a resistant structure to which cable attachments are fixed to enhance platform movement, while comfort issues are dealt with by a deformable cover that can adjust its shape to the limb. Safety is provided by keeping the cables movements from approaching the platform or intersecting each other or moving in front of the user's face. Adjustability of the interface is obtained by the sliding capability of the two parts comprising the interface platform.



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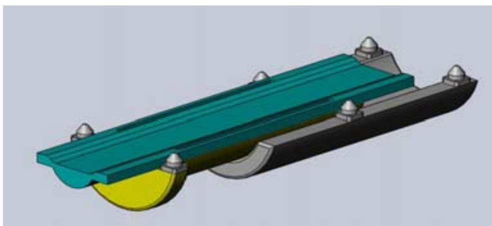

(b)

Fig. 14 A conceptual design for interface platform with adjustable characteristics. (a) A sketch; (b) A CAD mechanical solution

Fig. 15 shows a specific application of the platform interface for a human leg, using an additional frame for the stationary part of the leg. The idea here is to present an alternative way of fixing the lower extremity in an exercise machine. Usually, adjusting the axis of rotation with the patient' knee axis is not easy. Moreover, when the lower extremity is not well restrained, it can yield misleading measurements. Therefore, the proposed solution in Fig. 15 provides the additional advantage of restraining adequately the lower extremity, and can easily be adapted to any type of exercise. In the case of cable robots, the cables can be attached as shown in Fig. 14 to provide more precise determinations of leg movement by measuring 6 points simultaneously. A reduced number of cables can also be adopted. Concerning comfort, this type of attachment can be very comfortable if using cushioned lining, without altering the measurement precision since the leg is well secured to the frame where the points are attached. This will provide the necessary deterministic position of the attachment points for the cables but also comfort for the hosted leg.

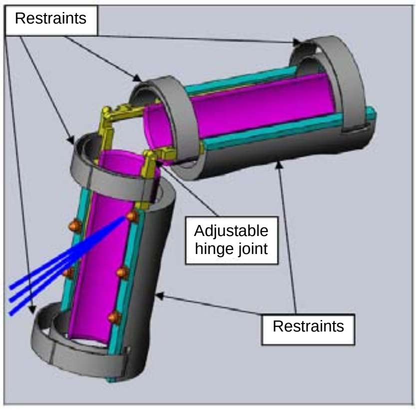

Fig. 15 A CAD design for using the design in Fig. 14 for full therapy exercise of a leg

For summarization, a human-machine interface for cable-based parallel manipulators can be designed for limb rehabilitation by considering its functionality, as from technical viewpoint, but also by taking into account comfort and safety issues through ergonomic designs together with constraints from medical protocols. The medical-oriented approach can guide the design, but also will in general constrain the solutions to designs in which the technical challenges are significant.

6 Conclusion

We have focused on the design problems for human-machine interfaces that must be used as end-effectors in cable-based parallel manipulators in physiotherapy applications. The discussion has outlined the main design considerations from technical viewpoints by taking into account users' constraints for comfort and safety.

A design procedure has been outlined as a result of a proper definition of the human-machine interface problem. Few design solutions for platform end-effectors in cable based parallel manipulators have simultaneously considered previous experience in the proposed conceptual discussion. As a final remark, it is noteworthy that the human-machine interface is a key aspect for the acceptance and success of cable-based parallel manipulators in medical applications and specifically in limb rehabilitation.

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