SPEXOR: Design and development of passive spinal exoskeletal robot for low back pain prevention and vocational reintegration

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Abstract

The objective of SPEXOR project is to address low back pain as one of the most appealing health problems of the modern society by creating a body of scientific and technological knowledge in the multidisciplinary areas of biomechanics, robotics, and computer science that will lead to technologies for low back pain prevention. In this paper we provide an overview of the current state-of-art of SPEXOR that the consortium achieved in the first twenty-four months of the project. After introducing the rationale, we describe the biomechanics of low back pain intervention, development of the musculoskeletal stress monitoring for assessment of neuromuscular trunk functions, modeling and optimization of the interaction of spinal exoskeleton with the human body, electromechanical design and development of the passive spinal exoskeleton and its control, and finally the end-user evaluation of the functional effects, usability and satisfaction.

Keywords Low-back pain · Spinal exoskeleton · Musculoskeletal stress

1 Introduction

Low-back pain (LBP) is often termed a pandemic of the modern world and represents great socioeconomic burden. Epidemiological studies have shown correlation between physically demanding jobs and prevalence of LBP, symptoms exaggeration and back injuries. Among these jobs handling heavy loads, repeated lifting and working time spent in flexed position are the most challenging. The objective of SPEXOR project is to address LBP by creating a body of scientific and technological knowledge in the multidisciplinary areas of biomechanics, robotics, and computer science that will lead to technologies for LBP prevention. In the following sections we provide an overview of the current state-of-art of SPEXOR that the consortium achieved in the first twenty-four months of the project.

2 Biomechanics of LBP intervention

Based on literature with regard to risk factors of LBP we established core requirements for each of the SPEXOR systems. These requirements included key variables to control, and their safety limits. Furthermore, using existing benchmark passive and actuated exoskeletons, we assessed how such systems interact with subject behavior in static trunk bending, dynamic lifting, and functional activities [1]. We found that current systems do reduce spine loading, especially during static work (Fig. 1). However, load reduction during dynamic lifting is insufficient, i.e. below 10%, and functional activities are hindered to some extent [2]. Additionally, current systems cannot be tuned to individual properties such as spine flexibility. These findings resulted in specific biomechanical requirements for the spexor passive and actuated systems.

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Fig. 1 Effect of a benchmark passive exoskeleton on subject-generated low back (L5–S1) moments (M_{pp}) during trunk bending with the hands at 100–0% of floor to upright stance hand height. Two moment-torque profiles result both in up to 20 Nm moment reduction

Iterative prototype testing is being performed in order to optimize the SPEXOR systems. Furthermore, based on parallel measurements of lab and mobile systems, we defined the optimum set of sensors, needed for real time monitoring of low back loading at the workplace [3, 4]. We subsequently tested the resulting SPEXOR sensor set under controlled conditions, and we found that it is capable of monitoring low back load with sufficient accuracy. At present, we are testing how real time feedback of such a system affects subject behavior and spine loading.

3 Musculoskeletal stress monitoring

One important aspect that is being researched in the project SPEXOR is a musculoskeletal stress monitoring system. With this monitoring system, it is possible to estimate biomechanical parameters such as joint angles and moments, especially from lumbar joints. This information it is used to send a feedback signal in critical situations. For example, when the person has surpassed an ergonomic limit during a working day. The monitoring system is based on inertial measurement units (IMU) place at different parts the human body, as well as force insole technology. These sensors are connected wirelessly to a base station. The system was designed to be robust, easy to wear and comfortable. The logistics industry is a good example of a use case scenario for this monitoring system. Lifting boxes is a typical scenarios in this industry (Fig. 2). Therefore, a biomechanical model was developed to identify the kinematics and dynamics of the movements done to lift a box [4–6]. This model is based on a rigid multibody system that solves the inverse kinematics and outputs the position and velocities of all degrees of freedom. The force insoles are used to provide the necessary information to solve the inverse dynamics, which gives the information of internal joint moments, i.e. to estimate the L5/S1 joint moments. For the system to work in a real scenario, the model has to be

Fig. 2 left: SPEXOR monitoring system used for a lifting scenario; middle: real-time model for estimating biomechanical parameters; right: example for retrieved data from the model like lumbar flexion angle over time

optimized for real-time operation taking into account the limitations of the wireless transmission from the sensors, of drifting of the IMU signals, and of the computer processing power. For the future, it is important to develop a parametrized model that can be customized to the height and weight of the user. This way it is possible to derive the length, mass, center of mass and inertia tensors of the segments using the regression method [7].

4 Modeling and optimization

In SPEXOR, model-based optimization is used as a tool to analyze and predict motions that are critical for the lower back and to design exoskeletons that best support such motions. For this purpose, we have developed subject specific multi-body system models describing various lifting and bending motions that take dynamic properties as well as characteristics of muscular joint torque generation into account. For describing the exoskeletons, a sequence of models with different components and free parameters has been established in the course of the project, to evaluate different design concepts for passive and active exoskeletons, involving rigid segments and bendable parts as well as compliant elements, damping and actuators in the joints. We have investigated two types of optimal control problems:

1. Optimal control for motion analysis: focusing on a tracking of recorded motions of healthy subjects without exoskeleton with combined human-exoskeleton models to explore how exoskeletons can provide maximum support for such standard motion patterns.
2. Optimal control for motion prediction: applying different objective functions such as a minimization of activation or a minimization of joint torques to predict motion trajectories for these behavior rules as well as

parameters and (in the active case) required motor torques of the exoskeleton.

In these models, the connection between human and exoskeleton model can be described by either constraint forces or compliant forces which both allow to analyze these interaction forces and limit them to stay below ergonomically acceptable constraints. Figure 3 shows two example models investigated. More details can be found e.g. in [5, 8] or [9]. Current research on modeling and optimization in the SPEXOR project involves inverse optimal control of patients with back pain, with the aim to identify behavior models in terms of optimality criteria for such patients with which further motion prediction and design optimization can be performed.

5 Electromechanics of spinal exoskeleton

Based on the musculoskeletal stress monitoring system as well as the robot-centred requirements for LBP intervention, we developed a passive spinal exoskeleton that achieves a similar range of motion as a human lumbar spine of up to 60° in the sagittal plane. We addressed this need by developing and testing a novel passive back support mechanism that consists of an elastic back support mechanism, the misalignment compensating hip module and a passive hip torque source. The elastic back support mechanism is comprised of flexible beams that run in parallel to the spine, providing a large range of motion and lowering the peak torque requirements around the lumbo-sacral (L5/S1) joint. The misalignment compensating hip module is a mechanism with three parallel hinge joints that compensate the misalignment and provides a good fit of the exoskeleton to the human body. Two torsional springs are mounted on the top two joints to avoid singularities and increase comfort. The passive hip torque source is a purely passive version of

Fig. 3 Examples for models of a passive (a) and an active (b) exoskeleton model investigated in SPEXOR

Fig. 4 Passive spinal exoskeleton with the elastic spinal module (a), the misalignment compensating hip module (b) and the passive hip torque source (c). Figure is adopted from [10]

the Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA 2.0) (Fig. 4).

6 Adaptive control architecture

The controller for engagement and disengagement of the hip spring is based on the probabilistic model of the human motion that classifies whether the user requires the support of the exoskeleton or the exoskeleton should remain disengaged to allow free motion [11].

Fig. 5 Block diagram of the control framework for the passive spinal exoskeleton

The control architecture has two main interconnected building blocks: safety and high-level control. The block diagram in Fig. 5 shows the connections between building blocks of the passive spinal exoskeleton framework.

Safety, as the primary concern of wearable robots, is ensured by monitoring both, the feedback signals and the control signals. The monitoring of both signals is based on an invariance control that supervise the nominal controller, and correct the control outputs if the system states are about to leave the admissible state-space region. Switching between the base and the corrective controllers ensure that the safety features are invariant. For the passive spinal exoskeleton, the safety is additionally ensured by also monitoring the feedback signal. If the feedback signal is within the permissible regions that can be achieved by the user, then the controller output u is enabled. The safety condition is governed by

$$u = \begin{cases} u, & \text{if } -20^\circ < q_t < 110. \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

where q_t is the upper body angle relative to the thigh. Note that this ensures that the feedback states are in the admissible set. Due to the mechanical characteristics of the passive spinal exoskeleton mechanism, the high-level control for the passive spinal exoskeleton can only account for uniformly reducing spinal load. The control to achieve this is given by

$$M_{exo} = uKM_h, \quad (2)$$

where M_{exo} is the moment component of the passive exoskeleton, u is the binary control signal that activates the clutches of the passive exoskeleton, K is a constant describing mechanical properties of the passive exoskeleton, M_h is the moment component of a human. The high-level control consists of two modes of operation: Manual and Automatic. In a manual mode user can freely chose to either engage or disengage the clutch. While in automatic mode, the control system automatically engages or disengages the clutch when needed. For example, when user is bending forwards the system will automatically engage the clutch at the beginning of the bend to provide support and reduce spinal loading. Similarly, when a user is walking, the system keeps the clutch disengaged to allow unconstrained motion.

7 End-user evaluation

To evaluate the applicability and user satisfaction of the to be developed SPEXOR exoskeleton in actual vocational and rehabilitation environments we organized focus group meetings with LBP patients, healthcare professionals and job coaches. In addition, we developed and tested protocols for evaluation of functional performance and user-satisfaction in work related activities. These protocols involve a wide range of functional activities that will be encountered in a working environment and that could either be assisted or hindered by the exoskeleton. Both objective (time/distance, physiological strain) and subjective (perceived task difficulty, discomfort, user impression) outcomes are included. These protocols were applied on a commercially available spinal exoskeleton (Laevo) to test the usability and reliability of the protocols and to create benchmark data for future SPEXOR devices [2]. Main conclusion of these preliminary tests were that the test protocols are adequate to evaluate trunk exoskeletons in terms of functional performance and user satisfaction. The benchmark test revealed that the exoskeleton tested could enhance performance in static forward bending positions. However, a decrease in task performance and increase in perceived task difficulty when wearing the exoskeleton in several tasks that required hip flexion was observed (Fig. 1). In terms of physiological strain, the exoskeleton reduced metabolic costs during lifting, but increased it during walking. Based on these benchmark tests with the Laevo exoskeleton we have been able to identify important design criteria for Spexor exoskeletons. The most important one is the disengagement of the device depending on the task performed, to support the spine when it is loaded but allow full range of motion in the hip in unloaded tasks. These design criteria are incorporated in the first SPEXOR prototypes. Using the developed protocols we are currently evaluating performance and user satisfaction for these first prototypes (Fig. 6).

8 Conclusion

This paper provides an overview of the current state-of-art of SPEXOR that the consortium achieved in the first twenty-four months of the project. In the future, our efforts will be dedicated towards the design and development of the active spinal exoskeleton that will address the current inabilities of the passive exoskeleton.

Fig. 6 Boxplots of perceived task difficulty. (The red line represents the sample median. The distances between the tops and bottoms are the interquartile ranges. Whiskers show the min and max values; outliers are represented as +). The dotted lines represent the division between the groups of tasks, in which the user is potentially assisted (left side), tasks, in which the user is potentially hindered by resistance against movement generated by the device (middle) and tasks requiring participants to use a large range of motion (right side). Brackets indicate significant differences between the exoskeleton (with) and control condition (without). 0 = very easy, 10 = very difficult

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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