THE IMPORTANCE OF STUDYING SAFE-FALL STRATEGIES FOR LOWER LIMB EXOSKELETONS

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INTRODUCTION

The ability to stand and walk usually plays an important role in performing activities of daily living and maintaining an independent life. However, mobility impairments impact many people's lives all over the world, and have significant effects on their quality of life. Mobility disability was identified as the most prevalent type of disability in the United States and the third most common disability in Canada (Courtney-Long et al., 2015),(Statistics Canada, 2013). Several diseases lead to mobility disability, and among those are injuries to the spinal cord, with a high prevalence of occurrence (Rosenberg, Bombardier, Hoffman, & Belza, 2011). Spinal cord injury (SCI) has various consequences such as motor and/or sensory deficits, often including partial or complete impairment with walking. As a result, assistive and rehabilitation technologies have been developed and used to help affected people maintain their independence and/or improve their functional mobility to perform activities of daily living.

To meet the growing need for effective assistive technologies and rehabilitation goals for people with lower limb impairments, the development of lower limb exoskeletons (LLEs) has gained more attention during the past few years (Dollar & Herr, 2008). LLEs have been designed to be used for both clinical and personal purposes. The results of previous studies show that LLEs, when used as therapeutic devices, can improve their users' health conditions (Chen, Chan, Guo, & Yu, 2013). However, safety concerns are still among the most challenging barriers to the acceptance and use of LLEs in the community. The FDA has identified "instability, falls, and associated injuries" as the primary risk associated specifically with these devices ("FDA news and events"). Thus, LLEs should be used under constant supervision and assistance from a trained companion according to FDA regulations ("CFR - Code of federal regulations title 21").

In the case where an internal or external perturbation is applied to an exoskeleton or the user, the exoskeleton's function might be perturbed, eventually leading to the destabilization and fall of the device and user. In the case of a fall with currently used exoskeletons, the impact velocity when hitting the ground is large enough to cause traumatic brain injury, bone fracture or bruises. In particular, a user is at risk of head injury during a backwards fall. Furthermore, normally persons living with an SCI have fragile bones, with low bone mineral density due to lack of physical movement. Therefore, the consequences of a fall could be even worse for these individuals (Bauman et al., 2012).

In one study where a LLE was used by a group of persons with SCI, the exoskeleton lost its balance 16 times, each time resulting in the engagement of a tether, which was used for safety considerations. The findings of this study confirm the risks associated with the use of LLEs (Kolakowsky-Hayner, Crew, Moran, & Shah, 2013). A survey of potential end users of exoskeletons and individuals who have experience working with mobility impairments reported safety to be the primary concern when using a LLE (Wolff, Parker, Borisoff, Mortenson, & Mattie, 2014). Addressing the safety issues associated with the use of LLEs is a top priority as these devices are expected in the future to assist individuals in performing activities of daily living independently. Therefore, the goal of this paper is to propose a strategy to enhance LLE user safety by reducing the risk and the severity of injury in the case of an unrecoverable loss of balance.

BACKGROUND

Fall-related studies in the field of exoskeletons are a relatively new area of research. In a recently published patent application, three protective strategies were proposed to be implemented in a LLE. The first strategy is to provide a cushioning mechanism that is used to absorb energy or spread the force at impact. The second strategy is to detect the state of imbalance and reduce the kinetic energy by generating braking torques at the joints of the exoskeleton. The third strategy proposed is a hybrid technique to use joint work to actively position the system during the fall to maximize the effectiveness of the cushioning mechanism (Angold, 2014). However, to the best knowledge of the authors, there has been no research or development of safe-fall strategies for the case of a human-exoskeleton fall. On the other hand, human-only and humanoid robot falls have been the focus of some studies during the past few years. These studies were reviewed to gain a better understanding of fall-related strategies among healthy individuals as well as bipedal robots.

Experimental work that studied the biomechanics of the human body during a fall reveal that people constantly use injury-mitigation strategies to reduce the occurrence of fall-related injuries (Lauritzen & Askegaard, 1992). Activation of the lower limb muscles throughout the fall was found to be one of the protective strategies that is employed by healthy individuals (Robinovitch, Chiu, Sandler, & Liu, 2000). Synergistic patterns of muscle contractions in the lower extremity lead to the application of braking torques at the lower limb joints. These torques are applied to the joints to resist the joint motion in the direction of the fall and lead to mitigation of the impact velocity. In the case of a backward fall, these synergistic patterns of muscle contractions are found to result in a series of body movements throughout the fall that end at ground impact while maintaining an upright torso (Tan, Eng, Robinovitch, & Warnick, 2006), (Robinovitch, Brumer, & Maurer, 2004).

The control systems of most humanoid robots are designed to maintain balance in the case where weak perturbations are applied to the robot. However, in cases of large disturbances, balance recovery techniques might not be effective and falls are inevitable. Due to the importance of preventing physical damage to the humanoid robots as well as considering human and environmental safety, safe-fall control strategies have been studied, developed and implemented in bipedal robots. In some studies, different numerical optimization techniques were used to develop control strategies in the case of a humanoid robot fall. The results of these works revealed less damage was transferred to the robot when safe-landing control strategies were used (K. Fujiwara et al., 2004),(K. Fujiwara et al., 2006), (K. Fujiwara et al., 2002).

METHODS

As mentioned previously, the main goal of this work is to propose strategies to enhance the safety of the exoskeleton users by reducing the risk and severity of injury in the case of a fall. The state of balance of the system should be monitored constantly by balance-detection algorithms and the use of available data from different sensors mounted on the exoskeleton. Different decisions could be made to handle the case when loss of balance is detected. First, a fall could be prevented by the application of balance recovery techniques. If this is successful, the exoskeleton would continue its function. However, if the application of a fall prevention strategy is not successful, the control system would switch to a safe-fall control strategy.

The data available regarding the mechanics of human and humanoid robot falls can provide the foundation for development of a safe-fall strategy for the case of a human-exoskeleton fall. Examining the human-only fall-related studies shows that healthy individuals successfully employ protective responses to diminish the intensity of a fall and, subsequently, the severity of potential injuries to the human body. More specifically, they try to achieve this by avoiding head impact and minimizing the impact velocity at the moment of ground contact. This is due to the fact that the severity of an injury is related to the velocity of the body segments at impact (Robinovitch et al., 2000). Safe-fall control strategies in humanoid robots, which were developed using optimization methods, were shown to have similar patterns throughout the fall as those movements employed by healthy individuals during a fall. According to the outcomes of these studies, in this paper it is proposed to use a numerical optimization technique to develop a control strategy in the case of a human-exoskeleton. The main characteristics of this safe-fall strategy are to avoid head impact and minimize the impact velocity of the body segments when hitting the ground. The following steps summarize the establishment of this proposed optimization methodology.

Step 1. Creating a model of a human-exoskeleton fall: In the field of biomechanics, it is common to represent the dynamics of the human body with a model of an inverted pendulum (Angeles, 2007). In this case, a model of a three-link inverted pendulum could be created in a simulation environment to characterize the dynamics of the human-exoskeleton fall.

Step 2. Formulating the dynamics of the fall: The equations of motion for the created model of a human-exoskeleton should be derived to describe the governing dynamics of the fall.

Step 3. *Defining the design variables*: These variables are being optimized throughout the fall to achieve the objective of the motion. They include the joint angles, angular velocities, and torques applied to the joints throughout the fall.

Steps 4. Defining the constraints: These constraints are mainly imposed by the biomechanics of the human body, the characteristics of an exoskeleton, and the environmental conditions. For example, they include the bounds on the joint angles and angular velocities, maximum/minimum available torque at the joints, and the ground surface condition.

Step 5. Defining the objective function: The objective function should be defined in terms of the design variables and describes the main objectives of this work, which are head impact avoidance and minimization of the ground impact velocity of the body segments.

Step 6. Selecting an optimization technique: An appropriate optimization method is selected based on the form of the objective function and the constraints that are required to be satisfied. For the model of a human-exoskeleton fall, the optimization problem is identified to be a multivariable, smooth, nonlinear, and non-convex optimization problem.

Step 7. Performing an optimization: After performing the optimization the optimal joint characteristics, including the optimal torque profiles, joint angles, and angular velocities that result in a safe-fall strategy are obtained.

Step 8. Validation: The results of the optimization should be validated before it is implemented in an actual exoskeleton. The two main validation techniques that could be used to verify the validity of the results are numerical validation (e.g., examining the robustness of the algorithm), and experimental validations (e.g., examining the feasibility of implementing the control strategy in a simplified prototype).

To further examine the validity and effectiveness of the optimal control strategy developed for the model of a human-exoskeleton fall, the characteristics of this control strategy could be compared with the main characteristics of a safe human fall strategy that include: rapid knee flexion at the onset of the fall, knee extension prior to ground contact, contacting the ground with an upright trunk with a near-zero trunk angular velocity to avoid head impact.

CONCLUSION

Current exoskeleton designs are susceptible to falls and causing injury to their users. The current state-of-the-art technology is not capable of safe and functional operation without external assistance, as there are no control strategies developed to safeguard the user and device against falling. Moreover, no safety considerations have been implemented on the exoskeletons currently being used that could lessen the severity of impact to the user in the case of a fall. This paper focused on eliminating this gap by proposing the development of a safe-fall control strategy to enhance user safety in the event of a human-exoskeleton fall. The motivation for this work is ultimately to improve the users' safety while wearing and using LLEs. The authors proposed the establishment of an optimization methodology to obtain the optimal joint trajectories of the human-exoskeleton model to avoid the risk of head impact and to reduce the risk and severity of injury by minimizing the impact velocity of the body segments.

Future work will focus on the development of the optimization methodology and a feasibility study regarding the implementation of this control strategy. It should be noted that the development and implementation of a safe-fall control strategy is a challenging problem. Numerous parameters are involved in the development of a safe fall strategy, including the characteristics of the device itself and environmental conditions (e.g., floor surface characteristics). Moreover, executing a safe-fall control strategy in a prototype or an actual exoskeleton would be a significant and complex challenge, and appropriate software and hardware platforms are needed to be able to successfully implement such a control strategy.

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