Bio-Inspired Impedance Controller and Balancing Feedback for the Effective Teleoperation of a Bipedal Robot

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Abstract— **This paper presents a novel bio-inspired controller for the online tuning of the joints impedance of a humanoid robot's arms while performing remote tele-manipulation. Emulating several behaviors observed in humans, the proposed controller accounts for the amplitude and direction of the interaction force developed at the end-effector as well as on the current arm configuration to autonomously adjust in real time the robotic arm impedance to the environmental demands. Experiments performed with the humanoid robot COMAN indicate that the proposed controller achieves a compliant behavior during collisions on the whole-arm while allowing for dexterous manipulations of different impedance environments. Additionally the integration of this local controller within the overall teleoperation framework is discussed. Of particular concern is the balance threat introduced by the impedance regulation. Indeed the joints stiffening behavior previously described allows for superior manipulation capabilities including heavy loads handling. However the large interaction forces induced may destabilize the bipedal slave. To address this concern an experimental study explores operators' ability to rely on a cutaneous feedback of the slave's balance state to adjust their teleoperation strategy when performing interaction tasks. Results clearly indicate that operators are able to rectify their teleoperated motions according to the vibrotactile guidance which appears thus as a mean to significantly reduce the number of falls and thus to increase the safety level.**

I. Introduction

The outstanding interaction skills exhibited by humans broadly stem from the ability to regulate their limbs impedance according to the task and the environment they are interacting with. Indeed the limb mechanical impedance, which characterizes the relationship between the displacement of the endpoint to the external forces required to effect this displacement, strongly influences the dynamics of physical contacts. Modulating this parameter appears as a strategy used by humans to successfully complete a wide range of everyday tasks including running [1] and jumping [2]. This phenomenon is correlated with different performances aspects. The resulting versatility allows alternating from a soft touch needed to manipulate delicate objects to a stiff behavior required to handle heavy loads or to apply high forces. Furthermore, different studies suggest that varying the limb impedance plays an essential role when performing explosive movement tasks [3] and serves to minimize the metabolic cost, that is to say to maximize the energetic efficiency, associated with the action performed [4]. The Central Nervous System (CNS) also takes advantage of the limbs stiffness regulation to control movements variability depending on the required accuracy [5].

Aware of the significant benefits offered by a proper impedance regulation, research efforts have attempted to transfer this skill to robotic systems. The impedance of a manipulator can be modified either physically through embedding elastic and/or dissipative elements at the hardware level, either virtually through varying the controller gains. Progresses towards passive variable compliance have been achieved with the development of both variable stiffness actuators [6], which mainly target safety improvements, and variable damping actuators [7], which have been proposed to regulate the oscillations induced by the joints elasticity. In parallel different strategies have been proposed to actively regulate the manipulator's impedance to meet the task requirements through emulating by software strategies the dynamical behavior of a spring-damper element with either fixed or variable gains [8]. In this work we propose to take advantage of both the passive and active compliance to achieve high performances during the teleoperation of the humanoid robot COMAN. Series elastic actuators mounted on 14 of the joints ensure a constant minimum level of compliance and serve to absorb the first force impact during physical collisions. Additionally the parameters of the dynamical response to joint trajectory errors induced by external perturbations are actively modulated by an autonomous impedance controller. The joints stiffening behavior leads to superior manipulation capabilities through enabling the slave to handle large loads. However, the development of high interaction forces may lead to the loss of balance of the intrinsically unstable bipedal robot. Considering that such catastrophic falls can be very damaging for both the robot and its surroundings, it is of the utmost importance to maintain the slave's balance during operations. Even though autonomous stabilizers constitute powerful modules to recover from external perturbations, they might result inadequate when considering a teleoperation scenario since the recovering strategy highly risks to conflict with the operator's intentions and cause the abortion of the task. In our approach we propose to integrate the operator in the loop through feeding back to him the balance state of the slave. The objective of the study is to evaluate whether operators are able to properly interpret this cutaneous feedback and to rely on it to alter their teleoperation tactic, in the same manner humans seamlessly adjust their strategy according to their equilibrioception to complete everyday actions without losing balance.

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This paper is organized as follows. In Sect. II the integration of the different modules within a unified teleoperation framework is discussed. The autonomous joint impedance controller is described in Sect. III. Section IV is dedicated to the analysis of the balancing feedback. Finally, Sect. V concludes this work.

II. Integrated teleoperation framework

Although humanoid robots have the technical capability to execute a large range of actions, the current progress in artificial intelligence is still far from providing adequate decision-making skills required to evolve autonomously in an unstructured world. An elegant way to overcome this difficulty consists in relying on the human intelligence and experience through teleoperation. However their large number of degrees of freedom together with their inherent instability make these systems difficult to control. Concurrently the remote environment's dynamical properties have to be infered from available feedbacks. The associated high cognitive workload may rapidly overwhelm the operator and induce severe performance degradations. Hence the need to develop a user-friendly teleoperation interface providing adequate assistance to operators.

A. Motion capture based position control

The control of the slave's stance is performed in an intuitive manner through tracking in real time the operator's wrists and torso position and orientation X_{op} using the vision-based motion capture system Optitrack from NaturalPoint, Inc [9]. The collected data is processed to generate the 6-DOF Cartesian trajectories of the slave's wrists and torso. The 29-joint trajectories q_d are then computed through inverse kinematics as illustrated on Fig. 2. This interface enables operators to easily control both arms, to make the robot squat as well as to bend the waist in any direction in order to extend its reachable workspace.
Relying on inverse kinematics to map a low-dimensional input to the robot's joint space rather than tracking a larger number of operators' body points allows to keep low the cognitive demand associated with posture control and is consistent with human natural motion control strategy. Indeed authors in [10] suggest that the CNS handles the complexity of the whole-body motor control through focusing on the trajectory of the most important point for executing the task, for instance the hand during reaching motions. This locus of attention is shifted whenever needed in order to accommodate the current task.

B. Autonomous impedance controller

Although there is a clear need for regulating the robotic device impedance to accommodate for the variations of the environment's impedance during the different phases of the task, the modality through which the target impedance should be defined remains an open problematic. Within the scope of teleoperation, two main possibilities appear to regulate the slave's impedance. The first one consists in relying on the operator to send the impedance reference through using a

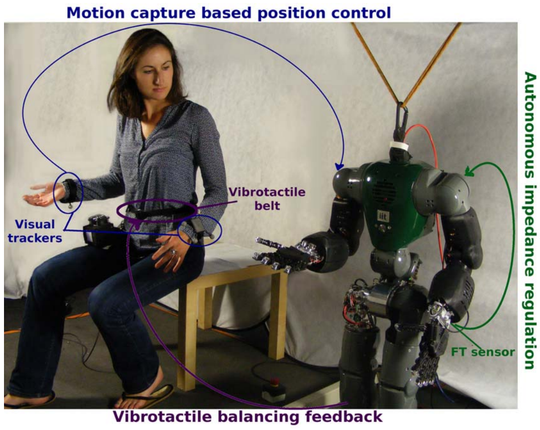

Fig. 1: An integrated teleoperation framework

dedicated input device such as a user grip force measurement unit [11]. A main drawback associated with this approach regards the additional cognitive load it induces for the operator who has to estimate the remote environment's characteristics in order to send the adequate impedance reference to the manipulator. Alternatively, we propose to transfer the impedance control to an autonomous module locally implemented at the slave side. Besides alleviating the operator from this concern, this solution is robust against eventual disruptions in the master-slave communication channel.
The proposed controller is thoroughly described in Sect. III.

C. Vibrotactile feedback

Maintaining the slave's balance while performing the task is critical but can result non trivial. Considering that the humanoid robot's balance is affected by its whole-body configuration and motion dynamics, which are directly controlled by the operator through the teleoperation interface, as well as by the interactions forces, which are governed by the manipulation strategy, we propose to investigate the benefits associated with a human-in-the-loop balancing strategy. The idea consists in monitoring in real time the balance state of the robot through evaluating its Center of Pressure (COP) position from the force/torque measurements at the robot's ankles and to feedback this information to the operator by the mean of a vibrotactile belt. A previous study [12] suggests that operators are able to properly interpret the cutaneous feedback when the slave evolves in free space. Experimental results indicated that operators were able to rectify their stance according to the tactile guidance so as to prevent the slave from reaching an inherently unstable posture, achieving a significant reduction of the number of falls. The aim of the present study is to determine whether this work can be extended to more complex situations involving interactions with the environment as discussed in Sect. IV.

III. Bio-inspired impedance controller

This section presents the bio-inspired local controller that autonomously modulates the slave joints impedance according to the interaction forces sensed at the end-effector. Subsection III-A describes the human behaviors that inspired the controller's design. Subsection III-B sets out the theoretical basis of the controller. Subsection III-C provides experimental evidences of the effective emulation of the human characteristics previously described by the robotic arm. A comparative study presented in Subsection III-D demonstrates the enhanced teleoperation performances achieved with the proposed controller during a lifting task.

A. A human-inspired impedance controller

Observations show that humans constantly modulate their limbs impedance while performing functional tasks. Such regulation, by modifying the body's response to external forces, allows to accommodate for the large range of impedances encountered in the real world, leading to stable interactions. Although the strategies used by the CNS to achieve this highly complex behavior are far from being completely understood, diverse studies have permitted to get an insight of some of the bio-mechanisms involved.

Manipulation dynamics are strongly affected by the mechanical impedance exhibited by the limb at the contact point. The elastic properties at the endpoint are governed by the joint mechanical structures, the stiffness of the muscles acting about these joints and the limb posture. In [13] authors reports that humans are able to modify their endpoint stiffness without modifying their limb geometry through the coordinated co-contraction of uniarticular and biarticular muscles. This regulation is orchestrated by the CNS to address environmental demands and has been shown to occur during position control tasks under perturbation force field as well as during force control tasks. In [14] authors report that the arm is selectively stiffened according to the direction and amplitude of the destabilizing force applied at the end-effector so as to stabilize the hand position. Diverse studies have been conducted to characterize this adaptive behavior at a lower level.

In [15] subjects behavior is analyzed during a postural task which consisted in controlling through a joystick the position of an inverted-pendulum subjected to a varying force field. To maintain the target position subjects had to reject perturbations through producing a resistive force in four directions. The joint stiffness-joint torque relationship has been examined through performing single and multiple linear regressions. Authors found that each coefficient of the 2x2 joint stiffness matrix varied with both the soulder and elbow torque. Also the bivariate model accounted for a slightly larger amount of variance in the data than the unvariate model, the shoulder stiffness coefficient appeared to be more strongly correlated with the shoulder torque than with the elbow torque and reciprocally the elbow stiffness was found to be more highly correlated with the elbow torque than with the shoulder torque.

In [16] a parallel study focusing on a force control task has been carried out. The elbow and shoulder stiffness are reported to vary linearly with respectively the elbow and shoulder torque but no significant correlation could be established between the elbow stiffness and the shoulder torque nor between the shoulder stiffness and elbow torque. On the basis of these studies we propose to use a univariate constant constraint between joint stiffness and joint torque such that each joint stiffness coefficient is linearly varied with the perturbation torque. The coefficient joint torque-joint stiffness is chosen constant so as to emulate the human behavior as described in [16]. Indeed experimental observations reported in this study reveal that during force-control tasks the joint stiffness is postural-dependent and the relation joint stiffness-joint torque is postural-independent. The implementation of the controller is detailed in the following section.

B. Implementation of the controller

Our approach consists in performing free-space operations with constant low impedance joints. The joint impedance regulation is triggered by the sensing of an external loading at the end-effector, indicating an active, task-related interaction with the environment. Joints are then selectively stiffened based on their contribution in countering the external force applied at the endpoint. The mapping from the end-effector loading to the joints loading depends on the direction and amplitude of the external perturbation as well as on the arm posture as described in Eq. 1.

$$\tau_{ext} = J^T(q)F_{ext} \tag{1}$$

with $F_{ext} \in \mathbb{R}^m$ the loading force in task space, $\tau_{ext} \in \mathbb{R}^n$ the joint torques and $J(q) \in \mathbb{R}^{mxn}$ the arm Jacobian. The joint stiffness gains are linearly increased with the component of the joint torque induced by the end-effector loading while a minimum stiffness is assigned when no external force is applied as formalized in Eq. 2.

$$K_s = \begin{cases} K_p \times J^T(q)|F_{ext}| & \text{if} \quad K_p \times J^T(q)|F_{ext}| \geq K_{si} \\ K_{si} & \text{otherwise} \end{cases} \tag{2}$$

with $K_s \in \mathbb{R}^n$ the vector of the joint stiffness gains, $K_p \in \mathbb{R}$ the torque-to-stiffness gain and $K_{si} \in \mathbb{R}^n$ the vector of the initial joint stiffness gains. In parallel the damping gains are modulated to keep each joint damping ratio constant during motion as described in Eq. 3, emulating the human strategy described in [17].

$$K_d = \alpha K_s \tag{3}$$

with $K_d \in \mathbb{R}^n$ the joint damping gains vector. The joint stiffness and damping gains are used to compute the joint reference torque which is then tracked with an inner PI loop. The proposed method consists thus in controlling the interaction dynamics through tuning the mechanical parameters of the response to trajectory errors as shown in Eq. 4.

$$\tau_{ref} = K_s(q_{ref} - q) + K_d\dot{q} \tag{4}$$

with $q_{ref} \in \mathbb{R}^n$ the reference trajectory in joint space as computed from the operator's motion, $q \in \mathbb{R}^n$ the actual joint trajectory and $\tau_{ref} \in \mathbb{R}^n$ the joint torque reference. The overall control scheme is presented in Fig. 2.

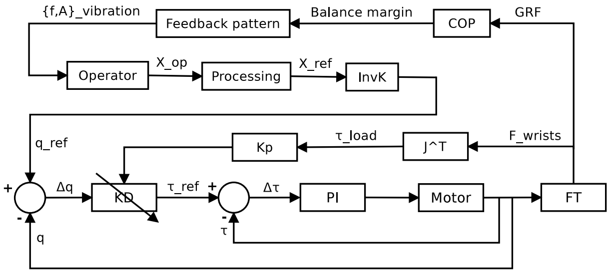

Fig. 2: Teleoperation control scheme

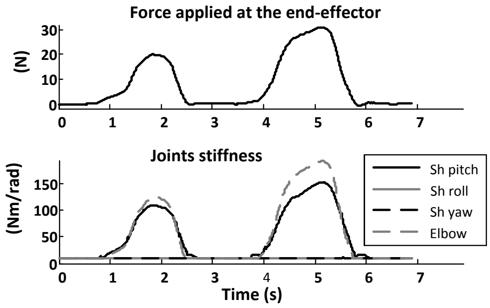

Fig. 3: Amplitude-dependent stiffening behavior

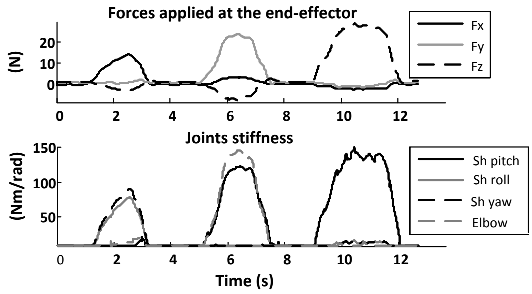

Fig. 4: Direction-dependent stiffening behavior

C. *Static postural task under external perturbations*

Experimental evidences of the behavioral characteristics achieved by the robotic arm under autonomous impedance regulation are provided in this section. They are obtained during a static postural task during which external perturbations have been applied on the arm.

* The joints impedance increases with the amplitude of the interaction force as shown on Fig. 3. Two forces of increasing amplitude are applied at the robot's wrist. The measured joint stiffnesses clearly show that the controller reacts with a scaled stiffening response.
* The stiffening behavior depends on the direction of the external force applied at the end-effector as illustrated on Fig. 4. External forces are successively applied at the robot's wrist along three orthogonal directions while the arm is maintained in a constant geometry. In response the joints are selectively stiffened based on their contribution to resist to the endpoint perturbation. For the arm posture used during the reported experiment, forces exerted along the x direction are withstood by an increase of the shoulder roll and yaw joints stiffness; forces applied along y are resisted thanks to an increase of the shoulder pitch and elbow joints stiffness while perturbations along z are countered through an increase of the shoulder pitch joint.
* The controller also accounts for the current arm configuration to selectively stiffen the joints withstanding the end-effector loading as demonstrated on Fig. 5. A vertical force is applied at the wrist for two arm postures. In the first configuration the controller stiffens the shoulder pitch and elbow joints while in the second configuration the stiffening behavior is mainly affects the shoulder yaw joint. The shoulder pitch and roll joints are also stiffened proportionally to their loading torque.

The previously described characteristics are intended to improve the robotic system manipulation capabilities through providing the slave with the versatility necessary to skillfully interact with delicate objects as well as stiff environments. An additional feature considered during the controller design regards the performances achieved in terms of safety. This aspect has become of primordial importance due to the recent changes of modern societies's expectations towards robotic systems. While automatised mechanisms have been so far contained to specific areas of industrial plants where safety precautions consisted in strictly isolating manipulators, new applications call for close human-robot coexistence. The entry of robotics systems in our unstructured and dynamically changing workspaces is conditioned to their ability to safely handle unforeseen collisions. The proposed approach consists in performing free-space operations, which do not require high position accuracy, with low impedance limbs. The resulting compliance leads to a soft behavior characterized by low contact forces during unforeseen collisions on the whole arm as illustrated on Fig. 6, 7. Moreover the initial low limb impedance leads to a soft behavior at the initial phase of contact at the endpoint. This allows to dramatically reduce the impact forces during involuntary contacts at the endpoint. Moreover this appears of major importance during intended contacts through ensuring smooth and stable transitions when at the initial contact with stiff surfaces.

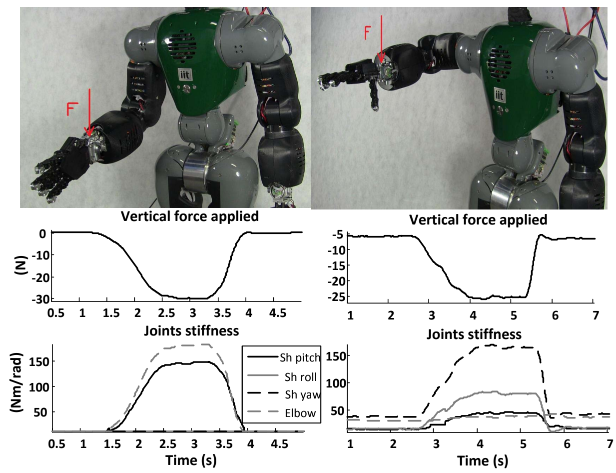

Fig. 5: Configuration-dependent stiffening behavior

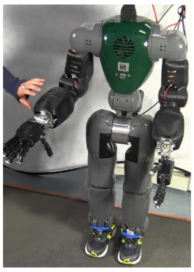

Fig. 6: Before contact

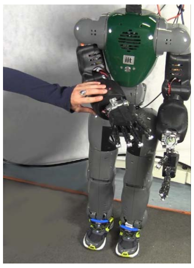

Fig. 7: After contact

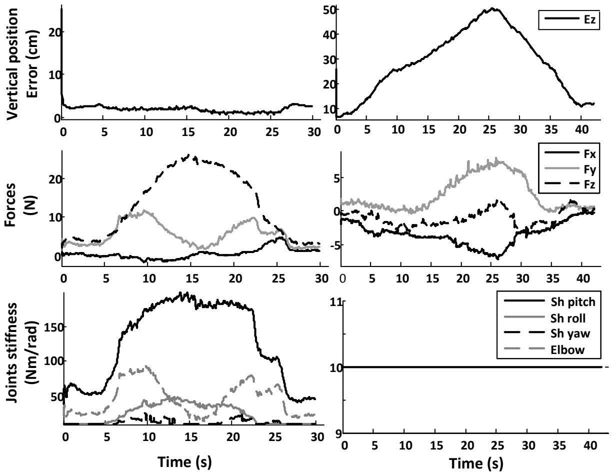

Fig. 8: Teleoperated lifting task with (left side) and without (right side) autonomous impedance controller

D. Joint impedance regulation during a lifting task

The performances of the impedance controller are also evaluated during a teleoperated task which consisted in lifting a 1kg load with the right hand of the robot. The vertical hand position error, the interaction forces sensed at the wrist and the arm joints stiffness are measured when performing the task with and without activating the local impedance controller. Experimental results are reported on Fig. 8. Under autonomous impedance regulation the slave successfully completes the task as indicats the small position error. In contrast, under constant low joint stiffness the slave is unable to develop the interaction force necessary to counter the load's resistance. As a consequence the tracking position error keeps growing up to 50 cm while the robot fails to lift the weight. This experiment clearly demonstrates the enhanced manipulation capabilities achieved through the autonomous joint stiffening behavior.

IV. Balancing feedback during contact task

In this section is evaluated the effectiveness of the vibrotactile balancing feedback to maintain the slave's balance during interaction tasks.

A. Vibrotactile feedback interface

To provide the operator with a directional cutaneous information, a four-tactor belt has been designed. Each tactor consists of an eccentric mass vibration motor mounted on a flexible rubber layer as shown of Fig. 9. The belt can

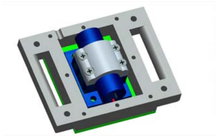

Fig. 9: Tactor

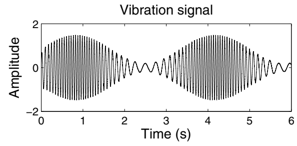

Fig. 10: Vibration signal

be easily adjusted to each operator's corpulence thanks to its variable-sized strip along which the vibrating modules can be slided in order to cover the front, back and sides directions. The vibration signal is expected to stimulate the phasic mechanoreceptors of the Pacinian corpuscule which are optimally activated by rapid vibrations (about 200-400Hz). Considering also that a constant amplitude signal can lead to a decreased perception of the spatial localization of the vibration source, the vibration signal is built as a variable high frequency sine wave carrier modulated by a low frequency sine wave signal as illustrated on Fig. 10. Both the amplitude and frequency of the vibration signal's envelope are increased when the stability margin of the robot decreases in one direction. Considering that the bipedal slave loses its balance when its COP reaches a boundary of the support polygon, the distance from the COP to the polygon's border is used to quantify the slave stability margin. This variable is then mapped to the vibration signal displayed to the operator according to a three-zones feedback pattern whose design is detailed in [12]. When the COP lies at the center of the support polygon no vibration is displayed whereas when the balance margin decreases the operator experiences successively two levels of vibration of increasing frequency and amplitude.

B. Experimental study

An experimental study has been conducted to investigate operators ability to adjust their teleoperation strategy according to the slave balance state during interaction operations. The task consisted in organizing 0.5kg and 1.5kg boxes into two piles situated in front of the robot (1) and on its left side (2). Carrying a load modifies the robot's COP such that its deviation from its initial position increases when the distance from the box to the robot's Center of Mass (COM) and/or the box weight increases. The distance from the robot's initial COM to pile (1) was larger than to pile (2) such that the heavy box could be placed only on top of pile (2) safely. Attempting to place it on top of pile (1) would make the robot fall forwards. By contrast, the light box could be placed either on pile (1) or (2) without loss of balance. Subjects were instructed to lift a box of unknown weight and try to pile it up on (1). In case they estimated that the robot could not perform this operation without losing its balance, they were enjoined to bring back the box close to the robot's COM and to place it on pile (2).
To understand the balance state of the humanoid robot, operators were provided with two different types of feedback: visual feedback only in one case, and visual + cutaneous feedback of the balance state through the vibrotactile belt

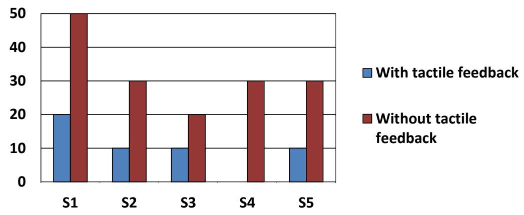

Fig. 11: Number of falls (%)

in the second case. The visual feedback was limited to the arm's workspace as would provide a head-mounted camera. To prevent operators to rely on any auditive cues from the joints motors, they were wearing hearing protection and a brown noise was displayed during the experiment. Five subjects took part to the study (four men and one woman) and performed a total of 20 trials (5 trials per condition). The different conditions (with/without tactile feedback, light or heavy load) were presented in a random order to reduce the learning effect. Performances were evaluated considering two factors: the number of conservative choices (placement of the light weight on pile (2)) and the number of falls when manipulating the heavy load.

C. Results

Experimental results reveal that conservative choices represent a marginal behavior with only one occurrence: operators tried to place the box on pile (1) when they judged that it could be done safely. The average number of falls under both feedback conditions is presented on Fig. 11. A paired-sample t-test for a two-tail mean difference indicates that the average number of falls is significantly lower under tactile feedback+visual feedback than under visual feedback only, $t(4) = 5.88, p = 0.0042 < 0.05$. This result suggests that the tactile feedback enabled operators to understand when the teleoperated robot's stability drops while interacting with the environment. Moreover they were able to rely on the cutaneous guidance to rectify their teleoperation strategy when required so as to maintain the slave's balance.

V. Conclusion

This paper presents an integrated framework for the intuitive yet effective teleoperation of a humanoid robot. A three-marker vision-based motion capture inferface is used to control the slave's whole-body posture. Considering the needs for a versatile behavior to dexterously interact with environments of highly diverse impedances, a novel bio-inspired controller is implemented at the slave side. Emulating various aspects of the human neuromotor control strategy, the proposed controller relies on the loading conditions at the end-effector to selectively tune the slave joints impedance so as to accommodate for environmental demands. Accounting for the direction and amplitude of the interaction force as well as for the arm posture, the controller uses a univariate constant constraint between joint stiffness and joint perturbation torque. Experiments performed with the humanoid robot COMAN indicate that the robotic slave achieves dexterous manipulations while exhibiting a compliant behavior during unforeseen collisions on the whole-arm as well as during the initial phase of contact at the end-effector.

The stiffening behavior provides the slave with the enhanced ability to develop high interaction forces. Although necessary to manipulate bulky objects, large contact forces may destabilize the intrinsically unstable humanoid robot. To address this concern a human-in-the-loop balancing strategy using the cutaneous feedback of the slave balance state is explored. An experimental study indicates that operators are able to recognize the slave stability drops during teleoperated interaction tasks. Moreover, results suggest that relying on the tactile guidance they are able to adjust their teleoperation strategy when required so as to maintain the robot's balance. The feedback of the slave's balance state is thus shown to lead to enhanced teleoperation performances characterized by a significantly lower number of falls than under visual feedback only.

Acknolegment

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