Demonstrating the Benefits of Variable Impedance to Telerobotic Task Execution

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***Abstract*— Inspired by human physiology, variable impedance actuation has been shown to benefit safety with its ability to modulate impact forces. But humans also continually adjust impedance during contact and throughout manipulation tasks. We examine the value and effect of continual impedance variation on quasi-static manipulation. We approach this challenge from the perspective of telerobotics where the operator can explicitly modulate the robotic impedance. Using a three degree of freedom planar teleoperation system we explore two quasi-static tasks: inserting a rigid peg into a tight hole and throwing a switch without overshoot. The work finds that no single impedance can optimally accomplish both tasks. Instead user-controlled impedance variations achieve the desired results, demonstrating the benefits of variable impedance to quasi-static applications in telerobotics.**

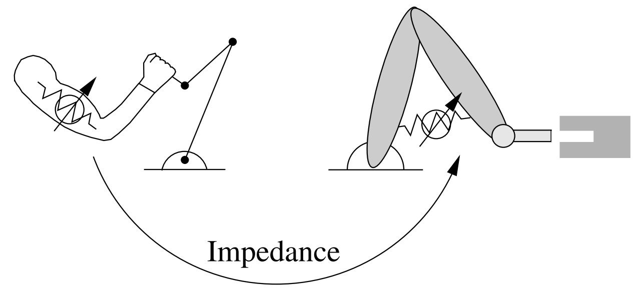

Fig. 1. Variable impedance manipulation involves continual adjustment of the robot's impedance throughout task execution

I. INTRODUCTION

With recent progress in robotics and telerobotics, there has been an increasing desire to operate robots in unstructured environments and alongside humans. To complete the required tasks both effectively and safely, it is often postulated that robots should have properties similar to humans when interacting with the external world. This is especially relevant to telerobotics, where the robot can be considered a stand-in for the human operator.

A particularly interesting human property is the ability to alter limb impedance through co-activation of antagonistic muscles pairs or through repositioning of the skeletal structure. This ability allows humans to adapt their interactions between firm and gentle, adjusting to both task requirements and environment conditions. It is believed that the inclusion of variable impedance, embedded in both actuation and control, would similarly allow a robot to interact more successfully.

Variable impedance actuators[1] have been shown to offer many benefits[2], especially to highly dynamic tasks. In particular, their advantages have been confirmed in safety applications [3], [4] through their ability to hide large actuator inertias and mitigate impact forces. Similarly, tasks requiring the storage and release of energy, such as running [5] and throwing [6], show significant performance improvements with such actuators.

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Variable impedance control can benefit less dynamic manipulation tasks. Humans modulate their impedance in response to different manipulation tasks, for example lowering stiffness when handling delicate objects or inserting a key into a lock. Other tasks, such as lifting heavy objects or drilling into hard surfaces, elicit muscle co-activation and high stiffness. For robots, impedance control[7] has championed the concept of a task-appropriate impedance for nearly three decades. Recent work[8] has extended this towards understanding and examining strategies for realtime and continual impedance variation.

In this work, we examine the value of impedance variability for quasi-static manipulation tasks. We approach variable impedance from the perspective of telerobotics where the operator can explicitly modulate the robot impedance. Previously we studied a single degree of freedom system[9] with mechanically variable impedance. Allowing the operator to continually adjust impedance promoted efficient strategies for the operator to regulate impact forces.

We create a planar three degree of freedom (DOF) teleoperation system and study two quasi-static tasks: inserting a peg into a tight hole and throwing a switch without overshoot. These tasks require substantially different impedances, representative of many manipulation requirements.

The work finds that no single impedance can optimally accomplish both tasks. Instead, providing the user continuous and direct control over impedance variations achieves the desired results, demonstrating the benefits of variable impedance to manipulation tasks in telerobotics. These findings have additional implications beyond telerobotics, both confirming the intuitive notion that variable impedance is advantageous for robotic manipulation and extending the known benefits of variable impedance actuators beyond safety and energy storage.

II. BACKGROUND

Early work on insertion tasks[10] found the forces experienced during peg insertion to be a function of the compliance matrix, positioning errors, clearance between the parts, and the friction between the pieces. It was also concluded that the center of compliance, and the lateral and rotational stiffnesses were important parameters for peg-in-hole interactions. Further work on the Remote Center of Compliance [11] describes the forces and moments experienced during peg insertion via the concept of a compliance center, positioning errors, misalignment, and the position and orientation stiffnesses.

Work in assembly and contact tasks has noted that robotic impedance should depend on the task, set either through impedance control[7] or with passive compliance[12], [13]. It is a natural extension to note that impedance should vary in realtime as task requirements change. Recent work on the realtime gain scheduling of impedance in automated systems[8] has been inspired by the ability of biological systems to continually adapt impedance, leading to robust, versatile interactions.

In general, programming the gain schedule for complex and varying tasks is a difficult problem. Human operators, though, have a great capacity for understanding the impedance appropriate to a given task as well as a strong ability to learn how to use tools provided to them. In previous work, we have given the human control of impedance scheduling in a 1-DOF system[9] in order to explore the benefits of impedance scheduling with a human in the loop. It was found that the human operator was able to adopt more natural strategies than those required by a fixed impedance device.

III. PLANAR TELEOPERATION SYSTEM

Complex manipulation tasks, such as aligning parts, require the coordination of position and orientation movements as well as their impedances. To capture this complexity, we use a 3-DOF planar system.

The slave device is shown in Figure 3. It includes three Maxon RE-35 motors with gear ratios of 113:1 at the shoulder and elbow joints, and 74:1 at the wrist. A 6-axis ATI Mini40 SI-100-5 force-torque sensor on the output link allows impedance control. The master device is shown in Figure 4. In this work the device is unactuated. A single-axis Honeywell Model 31 AL311BR load cell on the final link allows the sensing of user grip force. The entire system is controlled using realtime Linux with a 1 kHz servo cycle.

In connecting the master and slave we segment the controller into translation and orientation components, as shown in Figure 2. During the study, only the orientation impedance is modulated. This approach is motivated by the human wrist behavior during tasks similar to those in our study. By controlling wrist stiffness independently of limb stiffness, humans accurately perform a range of manipulation tasks. When inserting a key or wiggling a peg into a hole, the human approximately positions the key, but then presents a low wrist impedance to overcome misalignment. When writing, a human stiffens their wrist to aid in accurate position control of the tip of the pen. Additionally, the variation of only one system parameter, orientation impedance, allows us to more simply demonstrate and discuss the basic effects of varying impedance.

Translational control is achieved via a classic Jacobian transpose controller with fixed high impedance gains.

The orientation controller uses torque feedback to hide all internal friction with absolute stability[14].

$$\tau_\theta = \tau_d + 20\frac{s}{s+1.6\pi}\left(\frac{1}{s}\frac{\tau_d-\tau_e}{.04} - \dot{\theta}_s\right) \qquad (1)$$

This allows us to implement a wide range of orientation impedances without experiencing contact instability.

As mentioned previously, the master device is left unactuated in this work. In this way the slave impedance is wholly determined by the programmed impedance, and is not affected by the reflected user impedance. The user grips the end effector stylus similarly to a pen, and may command an impedance by regulating grip force. Specifically, grip force is scaled exponentially to set the wrist stiffness $k_{p,\theta}$. $k_{p,\theta}$ is saturated at the observed limits of usefulness and system capability in the range of 0.1 Nm/rad through 100 Nm/rad, with the former corresponding to a loose grip and the latter corresponding to a tight but not uncomfortable grip. Additionally, the wrist damping $k_{v,\theta}$ is scaled by the square root of the stiffness scale factor, maintaining a constant damping ratio over the stiffness range. The user wears headphones and watches the slave motion on a screen in front of them.

To demonstrate the benefits of variable impedance to task completion, we study two tasks which require differing strategies. The first task inserts a peg into a hole, which requires a compliant interface to prevent large forces and moments resulting from misalignment and positioning errors. The second task throws a switch between three positions. If the switch is to be turned on, it must be placed in its middle position, which requires precise positioning and disturbance rejection to accomplish.

IV. INSERTION TASK

Peg insertion is a task archetype that represents a variety of assembly tasks where two parts need to be mated or joined.

A. Task Requirements

Generally in insertion tasks, control of the robotic compliance is important to avoid forces that may jam the parts or damage them. The center of compliance should be near the hole interface and stiffnesses should be low to prevent misalignment and positioning errors from leading to large forces. [11], [10] describe the forces and moments experienced during peg insertion.

In contrast with automation, telerobotics allows a user to perform unprogrammed corrective actions during insertion. By jostling or moving the master laterally, the user can correct for position errors. If the orientation stiffness is high, the user must simultaneously rotate the master to overcome alignment errors. As both corrections need to be coordinated

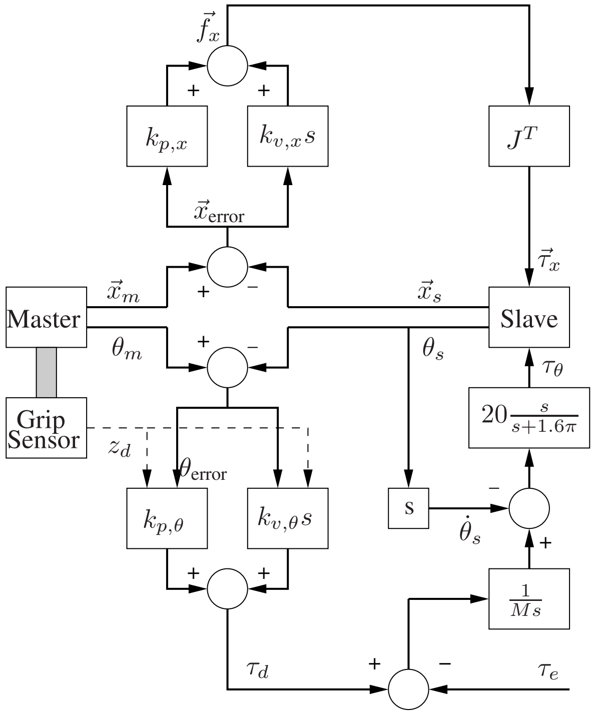

Fig. 2. Telerobotic architecture with separate control for position and orientation. The master is unactuated so that the low frequency slave orientation impedance is determined only by $k_{p,\theta}$ and $k_{v,\theta}$.

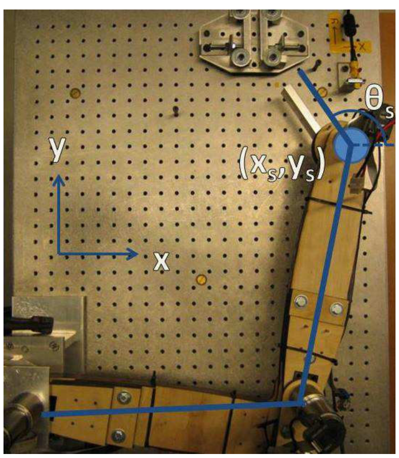

Fig. 3. Planar 3-DOF slave device with wrist mounted force sensor.

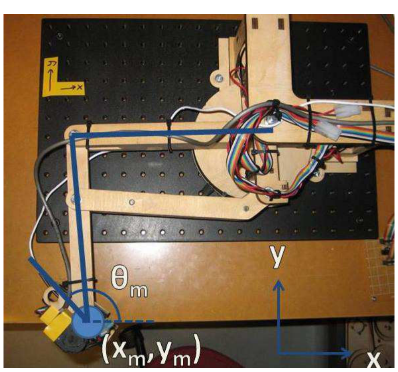

Fig. 4. Planar 3-DOF master device with grip force sensing.

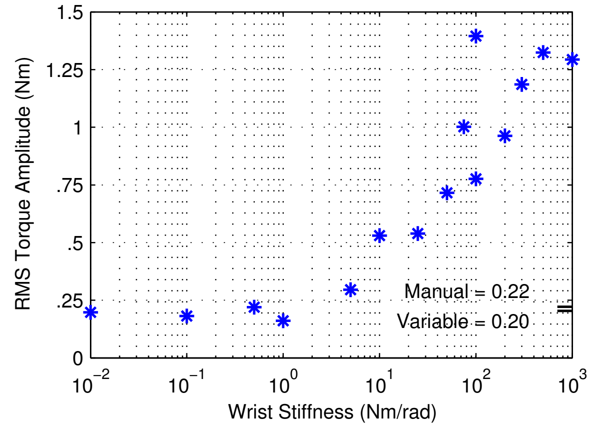

Fig. 5. Wrist stiffness $k_{p,\theta}$ versus RMS wrist torque τ_e during peg insertion shows that insertion torque increases with stiffness. RMS τ_e values for manual and variable impedance peg insertion are labeled and marked on the y-axis.

to prevent large forces or even peg jamming, task execution becomes difficult. Fortunately, if the orientation stiffness is low, the peg can align freely, reducing the coordination requirements on the user and allowing smooth insertion with smaller forces.

B. Experiments

We perform the peg in hole experiment by asking the user to touch a fixed point in the workspace, insert the peg until it is even with the back of the channel, remove the peg, and then touch the same fixed point. We perform this experiment with a trained user across a range of wrist stiffnesses $k_{p,\theta}$. We quantify the difficulty of the insertion by measuring the RMS wrist torque during the time in which the peg is in the hole. Figure 5 shows that as stiffness increases, the torque experienced at the wrist increases as well. Below some threshold stiffness, further benefits are no longer realizable.

Additionally, we had a human hold the robotic wrist and manually guide the peg into the hole over a number of trials. The resulting torque is marked on the y-axis of Figure 5. In trials with variable impedance available, the user minimizes torque by selecting low stiffness. That torque is also marked.

Figure 6 and Figure 7 show example traces for peg insertion. In Figure 6 with high stiffness, we see large torques and a stick-slip position trace as the forces build up and jam the workpiece momentarily. In Figure 7 with low impedance, we see smaller torques and a smoother position trace.

V. Three Way Switching Task

Throwing a three way switch to the center position requires positioning under sudden force changes. This task archetype lends itself to representation of any task requiring positioning and disturbance rejection.

A. Analysis

When throwing the switch, it will suddenly jump past the detent when the force applied F_{switch} is greater than a threshold F_{required}. As shown in Figure 8, the switch must

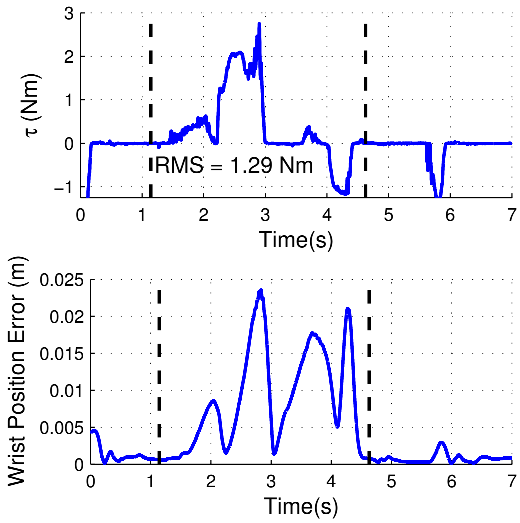

Fig. 6. Wrist torque τ_e and position error $|\vec{x}_{error}|$ during typical high impedance peg insertion shows stick-slip and jamming in the position trace.

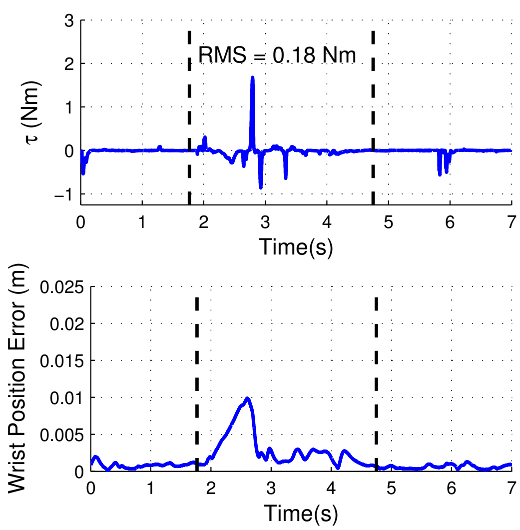

Fig. 7. Wrist torque τ_e and position error $|\vec{x}_{error}|$ during typical low impedance peg insertion shows smaller insertion torques.

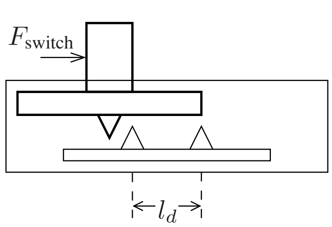

Fig. 8. Three way switch schematic.

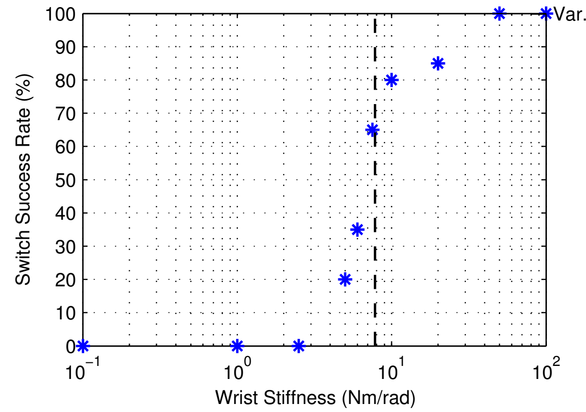

Fig. 9. Switching success percentage increases with wrist stiffness $k_{p,\theta}$. The predicted value of stiffness required is marked as a vertical line. Variable impedance had 100% success, as marked on the y-axis.

be placed inside a small range of width l_d. If we have an end-effector position error Δx more than l_d, then the slave may gain momentum capable of jumping the second detent.

Given an endpoint impedance k, the applied force is

$$F_{\text{switch}} = k(\Delta x) \tag{2}$$

For a Δx less than l_d with $F_{\text{switch}} < F_{\text{required}}$, we need

$$k > \frac{F_{\text{required}}}{l_d} \tag{3}$$

For our experimental setup, with an endpoint lever arm l in the final link, the required orientation stiffness is

$$k_{p,\theta} > \frac{F_{\text{required}}}{l_d} l^2 \tag{4}$$

In our system, the threshold force is 2.5 N, the detent width is 5 mm, and the end-effector has a lever arm of 12.5 cm. Thus the required stiffness for throwing the switch successfully is $k_{p,\theta} >$7.8 Nm/rad.

B. Experiments

We perform switch experiments by having the user touch a fixed point in the workspace, then throw the switch from position 1 to position 2, and touch the fixed point. While in position 2 the switch lights an LED to alert the user that the switch is correctly positioned. If the switch remains in position 2, the trial is a success. If the switch is thrown to position 3 the trial is a failure.

A trained user performed this experiment twenty times at a range of stiffness values, and Figure 9 plots the results. We see that at low stiffness the user has trouble throwing the switch, as a large position error must be created with a large amount of stored energy. At high stiffness the device acts as a position source and the user has no trouble throwing the switch. A threshold is crossed at the predicted stiffness where the success rate increases quickly, marked as a vertical line. With variable impedance, the user was able to achieve a 100% success rate, as marked on the y-axis.

VI. Combined Task Performance Experiments

We have seen that the choice of stiffness affects each task. Higher stiffness leads to higher insertion torques, stick-slip, and occasional jamming, but allows the user to accurately throw the switch. Lower stiffness reduces insertion torques and makes peg-in-hole smoother, but makes it difficult to accurately throw the switch.

To explore the implications of these results, we ask the user to perform both tasks in succession. The user must touch a fixed point in the workspace, insert the peg, throw the switch from position 1 to position 2 and then touch another fixed point. The value of $k_{p,\theta}$ will be important in shaping the user's ability to perform this combined task.

Looking at Figure 5 and Figure 9, we try to select a compromise value of $k_{p,\theta}$ which allows adequate performance of both tasks. We note that a $k_{p,\theta}$ value of 10 Nm/rad allows the user to throw the switch with approximately 80% success while experiencing peg-in-hole torques of only 2 to 3 times the minimum. We select this as the best fixed value of $k_{p,\theta}$, allowing completion of both tasks.

However, we note that no single impedance leads to the best execution of both tasks. Choosing a compromise $k_{p,\theta}$ value allows adequate completion of both tasks, but not to the full extent of the system's ability. If we allow the user to vary $k_{p,\theta}$, they will be able to adjust their strategy to the current task, allowing the user to perform peg-in-hole with the minimum torques and throw the switch with the highest possible accuracy. With low stiffness, the user is de-emphasizing tracking and focusing on careful force modulation and with high stiffness, the user is favoring position control and disturbance rejection. For these specific tasks, the lowest possible stiffness is required during peg insertion and a high stiffness is needed during switching.

A. *Experiments*

Figure 10 shows performance of the combined task at high, medium, low, and variable impedances. Each trace highlights the insertion and switching phases. The medium impedance is the optimum fixed impedance chosen previously. At high impedance, peg insertion leads to large torques, but a small position error is experienced during switching. At low impedance, the user cannot throw the switch due to the large position error, but smaller torques are encountered during peg insertion. The best fixed value of $k_{p,\theta}$ experiences intermediate levels of torque and position error. The switching position error ($12.5\ cm \cdot \theta_{error}$) approaches the 5 mm detent width, suggesting that lowering $k_{p,\theta}$ further would lead to an inability to reliably throw the switch. Finally, using variable impedance, the user employs a strategy which first uses medium or high impedance to align the peg with the hole, and then the lowest available impedance to overcome alignment error during insertion. Finally, the user employs a high impedance in order to accurately throw the switch.

We collect these results in Figure 11, computing the RMS torque during peg insertion and the RMS orientation error during switching. We see the clear tradeoff associated with fixed impedance levels. Only the variable impedance can accomplish both tasks well, with small insertion torques and precise positioning while throwing the switch.

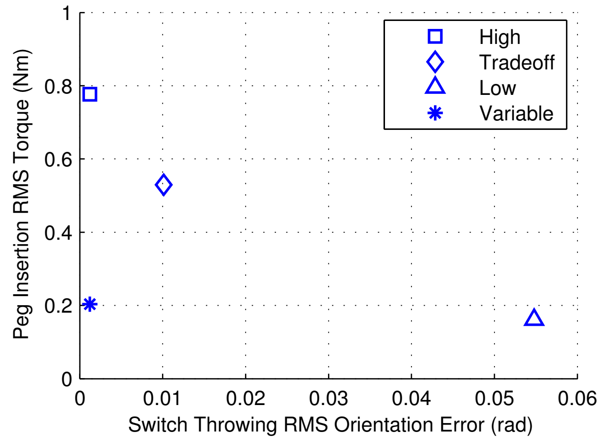

Fig. 11. Relative performance of the impedance configurations quantified via RMS τ_e during peg insertion and RMS θ_{error} during switch throwing. Variable $k_{p,\theta}$ achieves the best performance possible in both tasks.

VII. Conclusions

We have demonstrated that no single impedance allows the user to perform a range of tasks to their best possible level. Instead, allowing realtime impedance changes in response to user input allows the full realization of the telerobotic system's potential.

In particular, we have illustrated this concept by using a 3-DOF planar telerobotic system to perform peg-in-hole and precise switch-throwing tasks. The peg-in-hole tasks are more easily performed with a compliant interface, while accurate positioning of a three-way switch requires a stiff interface. We have shown that no intermediate value of interface stiffness allows the best possible execution of both tasks. Allowing the user to adapt the interface compliance to suit the current task allows the execution of both tasks to the full capability of the system. This result further confirms the benefits of impedance variation in general robotic manipulation, where a programmed intelligence can command a task-specific impedance.

We note that impedance is a frequency-dependent quantity. It can be affected by impedance control up to a certain closed-loop bandwidth, and it can be altered by hardware across the entire frequency spectrum. We envision implementing variable impedance in hardware, ultimately combining the presented benefits during quasi-static tasks with safety and energy storage benefits.

We conclude that telerobots and robots in unstructured environments encountering a range of tasks will have more success when equipped with a variable impedance interface than with any choice of a single, fixed-impedance. In telerobotics, enabling explicit user control over the robot impedance provides efficient task strategies. For these reasons, variable impedance should receive strong consideration in future robotic system designs.

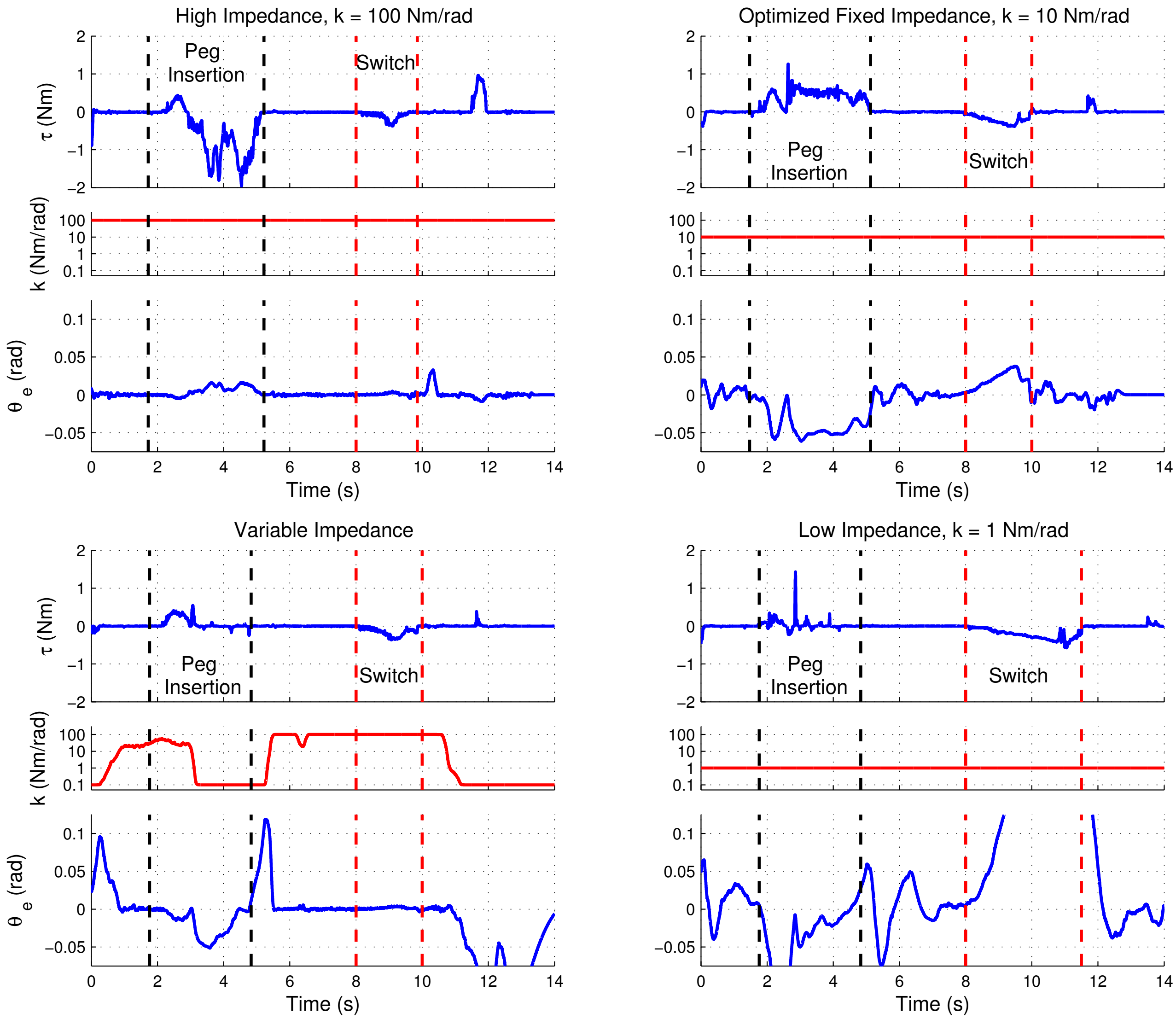

Fig. 10. Wrist torque τ_e, stiffness $k_{p,\theta}$ and orientation error θ_{error} during combined task execution for high, medium, low, and variable impedance. Vertical lines highlight insertion and switching tasks. Only variable impedance achieves the lowest insertion τ_e and smallest switching θ_{error}.

ACKNOWLEDGMENT

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