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Gradual anisometric-isometric transition for human-machine interfaces

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***Abstract*— Human-machine interfaces (HMIs) are widely used in biomedical applications, from teleoperated surgical systems to rehabilitation devices. This paper investigates a method of control that allows an HMI to transition from anisometric to isometric mode, shifting the control input from position to force as the user's movement is gradually reduced. Two different approaches for achieving this transition are discussed: one is based on the natural system dynamics, whereas the other involves selecting and controlling dynamics. The two approaches were implemented on a custom haptic device in a targeting task. Anisometric to isometric transitioning can potentially be used for training purposes, enabling transfer of what was learned in one mode to the other, as well as novel studies of the human sensorimotor system.**

I. INTRODUCTION

Human-machine interfaces (HMIs) have a variety of biomedical applications, including teleoperated surgical systems, haptic simulators for clinical training, movement therapy for neuro-rehabilitation, and prostheses. Proficient use of an HMI requires users to learn the mapping between their physical input to the control interface and the output of a controlled object, such as the position of a teleoperated robot or a cursor in a virtual environment. Depending on the application, different types of HMIs and corresponding controllers may be more effective in achieving good performance and facilitating user learning. Knowledge of human sensorimotor capabilities can motivate the design of HMIs, and HMIs can in turn be used to learn more about the sensorimotor system, such as motor adaptation or the role of proprioception.

HMIs can be divided into two categories: isometric and anisometric. An isometric interface does not allow movement of the user; applied force/torque is the control input. This feature allows the HMI workspace to be small, while enabling the user to manipulate a controlled object in an infinitely large workspace without having to re-clutch. It has also been suggested that isometric interfaces can reduce user fatigue [1]. However, the lack of proprioceptive cues (sense of body position) is thought to make isometric interfaces less intuitive.

In contrast, an anisometric interface allows movement, with varying degrees of resistance, and can use displacement as the control input. The inherent impedance of the device can be altered, via standard impedance or admittance control, by implementing position-, velocity-, and/or acceleration-dependent resistive forces. In the extreme case in which there is little or no resistance, the interface is said to be isotonic or free-moving. While anisometric interfaces have the benefit of providing proprioceptive feedback, this may require a more costly and mechanically intricate device.

The user's control input $\mathcal{I}_u$, which can be a force (or torque) f_u or displacement x_u, can be directly or indirectly mapped to the position of the controlled object. Two common control schemes are position and rate control:

$$\mathcal{I}_u = k_{pos} x_c \tag{1}$$

$$\mathcal{I}_u = k_{rate} \dot{x}_c \tag{2}$$

where x_c and $\dot{x}_c$ are the position and velocity of the controlled object, respectively, and the units of the gains k_{pos} and k_{rate} depend on the type of control input. Previous work suggests that rate control is more compatible with isometric devices, whereas position control is better suited for isotonic devices [2], [3]. These two control methods have been shown to produce comparable user performance, although isometric rate control has a steeper learning curve [2].

Previous work has focused on comparing the two extremes of isometric and isotonic devices, in addition to elastic devices (self-centering anisometric devices with position-dependent resistive forces). Researchers have studied the effects of control gain and elastic resistance ranging from isotonic to nearly isometric [4], [5]. Other studies have compared position tracking performance under different resistive forces [6], [7], yet few have made comparisons to equivalent isometric controllers [8]. Additionally, such experiments have only examined a few intermediate values, rather than a gradual and continuous transition between the two extremes of isotonic and isometric control.

This paper investigates two approaches that allow an HMI to continuously transition from anisometric to isometric mode, shifting from the use of position to force (or vice versa) as the control input. This allows users to gradually transition between the two extreme cases, or select a desirable movement ratio for operation. Such an interface has the potential to be used as a training device, enabling transfer of what was learned in one mode to the other, and may allow for new ways to study the human sensorimotor system.

II. CONTROLLER DESIGN

We have designed a controller to transition a device between anisometric (isotonic, in the ideal case) and isometric mode, gradually shifting between control inputs and altering the amount of movement allowed to the user. At one extreme,

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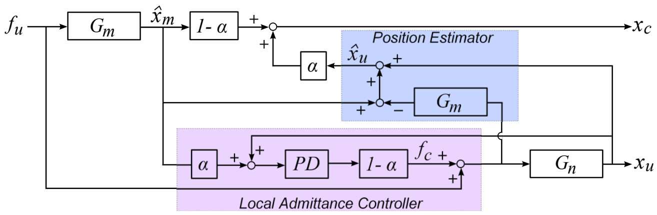

Fig. 1. Approach 1 (Natural dynamics) is driven by the inherent dynamics of the system G_n. When $\alpha = 1$, the user's movement x_u, and subsequently the controlled object's movement x_c, is determined by the user's force f_u and G_n. An appropriate model G_m is then chosen to ensure a smooth transition to isometric mode. The local admittance controller uses a proportional-derivative (PD) controller.

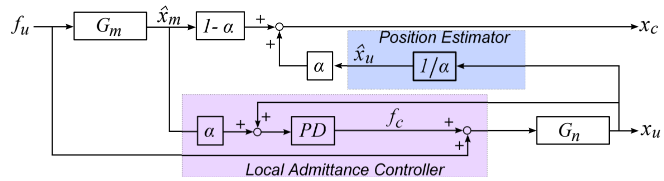

Fig. 2. Approach 2 (Selectable dynamics) is driven by the desired transfer function between user's force f_u and controlled object's position x_c in isometric mode. When $\alpha = 0$, the controlled object's position x_c is determined by the user's force f_u and the chosen model G_m. The local admittance controller is used to impose model dynamics G_m on the device.

the user's position is the control input, directly corresponding to the position of the controlled object via position control. At the other extreme, the user's forces are mapped to the position of the controlled object via some transfer function. The goal of this research was to develop a method to ensure a smooth transition between these two operational modes. Fehlberg et al. [9] developed a controller that also uses a combination of the user's force and position to control a device, but the user's movement is always isotonic.

When using an anisometric device (excluding trackpads), a variety of kinesthetic information is present, including proprioception and forces. Proprioception, however, is absent when the device is in isometric mode. Thus, we designed the controller with the intent of maintaining the same relationship between the user-applied force and the controlled object's position, even when the control input is position. Similarly, Notterman and Page [8] compared tracking performance of an anisometric device with second order dynamics and an isometric device with the same second order transfer function relating force to an output position. However, they did not transition between the two control modes.

A. Approach 1: Natural dynamics

1) Block Diagram: One possible approach to accomplish a continuous transition between anisometric and isometric control is shown in Fig. 1. In isotonic mode ($\alpha = 1$), movement of the device, and thus the user's position x_u, is determined by the inherent dynamics of the device and user G_n. The controlled object's position x_c is solely controlled by the user's position, using (1) where $k_{pos} = 1$. In order to maintain an equivalent transfer function between the user's force (or torque) f_u and x_c, the dynamics of the system must be approximated by some model G_m. The G_m transfer function is used to compute $\hat{x}_m$, an estimate of the user's position under isotonic mode ($\alpha = 1$) assuming the same force f_u is applied. In isometric mode ($\alpha = 0$), the user's position is held stationary and x_c is solely controlled by $\hat{x}_m$, as determined by the user's force. The resulting isometric control scheme may take the form of:

$$f_u = m\ddot{x}_c + b\dot{x}_c \tag{3}$$

where m and b are the mass and viscous damping coefficient of the system, respectively.

When $0 < \alpha < 1$, the device is in anisometric mode, although the resistive forces are not directly proportional to kinematic parameters (as in the case of a purely elastic interface). The *Local Admittance Controller* restricts the user's movement, applying a force f_c such that the user's position tracks a scaled $\alpha\hat{x}_m$ to varying degrees. The amount of influence f_c has on the user's movement is determined by the $1 - \alpha$ term. During the transition period, the position of the controlled object is a weighted average of $\hat{x}_m$ and $\hat{x}_u$. $\hat{x}_m$ and $\hat{x}_u$ both estimate the same value, with the difference being that the $\hat{x}_u$ approximation uses both the measured user position x_u and user force f_u, rather than just f_u. This is accomplished via the *Position Estimator*, which uses the model G_m to estimate how much f_c restricts the user's movement, then adds this to the actual user movement.

2) Simulations: We simulated Approach 1 for a one-degree-of-freedom rotational system with dynamics given by (3). For each value of α, the simulated user applies the same torque f_u to the device, resulting in the subsequent motion of the user x_u and controlled object x_c. For the simulations shown in Fig. 3a, it is assumed that the system is perfectly modeled, such that G_n and G_m are equivalent. Thus, the same torque applied by the user, regardless of how much the user physically moves as the value of α changes, results in the same observed movement of the controlled object.

The simulations shown in Fig. 3b assume that there is a discrepancy between G_n and G_m, representing a realistic scenario in which modeling errors underestimate the mass by 10%. The controlled object's movement in isometric mode, and for all cases when $\alpha < 1$, is thus greater than its movement in isotonic mode, although the user applies the same torque. In other words, the transfer function relating the user's torque and the controlled object's position gradually changes with α.

B. Approach 2: Selectable dynamics

1) Block Diagram: An alternative approach (Fig. 2) is to first select the desired model transfer function G_m, relating user force (or torque) f_u to the controlled object's position x_c in isometric mode, rather than having it depend on the system's natural dynamics as in Approach 1. Thus, G_m may be of the form (1), (2), (3), or some other variation. Isometric mode ($\alpha = 0$) for both approaches remains the same, where x_c is controlled by the user's force via the model G_m. When

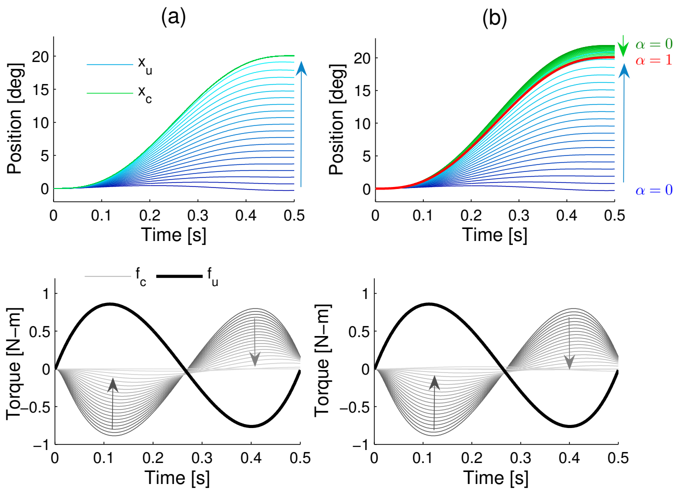

Fig. 3. Simulations of Approach 1 (Natural dynamics) when (a) G_m equals G_n and (b) G_m underestimates the G_n mass by 10%. The user always applies the same torque f_u (thick black, bottom plots). The position of the user x_u and controlled object x_c (blue/green, top plots) and controller torque f_c (grey, bottom plots) are shown throughout the transition from isometric to isotonic mode (α increases with arrow direction). For (a), the x_c trajectories are overlaid on one another. For (b), the thick red line is when x_u equals x_c in isotonic mode.

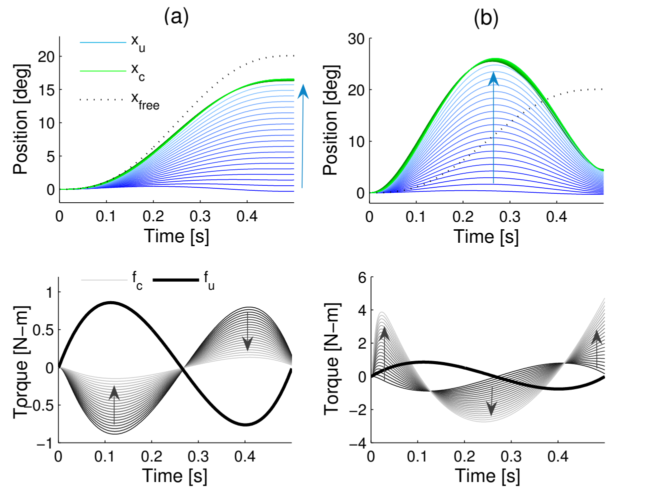

Fig. 4. Simulations of Approach 2 (Selectable dynamics) when the model G_m (a) is of similar form (3) to the natural dynamics G_n, and (b) is of form (2). The user always applies the same torque f_u (thick black, bottom plots). The user's position x_u, controlled object's position x_c, and controller torque f_c are shown as α transitions from 0 (dark blue/green/gray) to 1 (light blue/green/gray). The device would typically follow the x_{free} trajectory (dotted black, top plots) given f_u and its natural dynamics G_n.

$\alpha = 1$, x_c will similarly be directly controlled by the user's position x_u, but the device will be commanded to move with the dynamics specified by G_m. This is accomplished by removing the $1 - \alpha$ term from the *Local Admittance Controller*. Thus, the device may no longer act as an ideal isotonic device when $\alpha = 1$, but is still anisometric.

This second approach greatly simplifies matters during the transition period, when $0 < \alpha < 1$. The *Local Admittance Controller* restricts the user's movement by having x_u precisely track $\alpha \hat{x}_m$. As with the first approach, the *Position Estimator* uses the measured x_u to provide an estimate of the user's position in the case when $\alpha = 1$, assuming the same force is applied. However, since the behavior of the device when $\alpha = 1$ is determined by G_m, and x_u is set to track $\alpha \hat{x}_m$, $\hat{x}_u$ is simply $\frac{1}{\alpha} x_u$.

2) Simulations: Simulations of Approach 2 use the same system dynamic parameters as in the Fig. 3 simulations. In Fig. 4a, the model transfer function G_m is of the same form as the system's natural dynamics G_n (3), but G_m parameters m and b are chosen to be 30% and 25% greater than the system's mass and viscous damping coefficient, respectively, to greatly alter the system's natural dynamics. Thus, when $\alpha = 1$, the controller essentially implements impedance control [10]. If the user were to apply the torque f_u without the controller in effect, the user's position would instead be x_{free}.

In Fig. 4b, G_m is of form (2), where f_u is the control input $\mathcal{I}_u$. In isometric mode, x_c is controlled using rate control. As a result, the device essentially operates as an admittance device when $\alpha = 1$, where the user's force is mapped to the velocity of the device.

III. Implementation and Results

The two approaches were implemented on a custom one-degree-of-freedom rotational haptic interface for the index finger (Fig. 5a), previously developed for proprioception experiments [11]. The backdrivable device transmits torque from a DC motor to the MCP joint of the finger, and the system displays a graphical version of the finger at the same scale on a computer screen. To implement Approach 1 (Natural dynamics), system identification was performed by manually applying torques to the isotonic device, measured by a force/torque sensor, and estimating the dynamic parameters by ordinary least squares. The dynamic equation used was of the form of (3), with an additional Coulomb friction term c. The best fit parameters were: $m = 0.000034$ kg-m^2, $b = 0.000053$ N-m-s/deg, $c = 0.035$ N-m (G_{m1}). When the user's torque was input to the model, the resulting position did not correspond well to the actual device position (results not shown). Since an accurate model is desirable for implementation of Approach 1, system identification was again performed while a computer-generated damping force ($b_{add} = 0.00005$ N-m-s/deg) was applied to the device, resulting in best fit parameters: $m = 0.000024$ kg-m^2, $b = 0.00055$ N-m-s/deg, $c = 0.023$ N-m (G_{m1add}). Model G_{m1add} produced better correspondence, although it was still sensitive to the accumulation of error over time, and was thus chosen to implement Approach 1. However, this required the additional damping force b_{add}, so the device was never truly isotonic, even when $\alpha = 1$.

Approach 2 (Selectable dynamics) was implemented using G_{m1}, position control (1) with $k_{pos} = 80$ N-m/deg (G_{m2}), and rate control (2) with $k_{rate} = 650$ N-m-s/deg (G_{m3}). PD controller gains were chosen to maintain good tracking and stability.

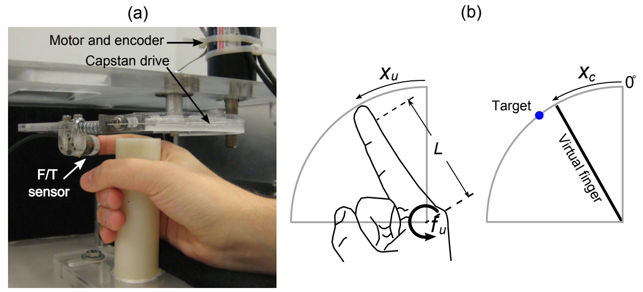

Fig. 5. (a) Custom haptic HMI measures angular finger position (via encoder) and applied torque (via force/torque sensor). (b) The user's torque f_u and finger position x_u control the virtual finger position x_c.

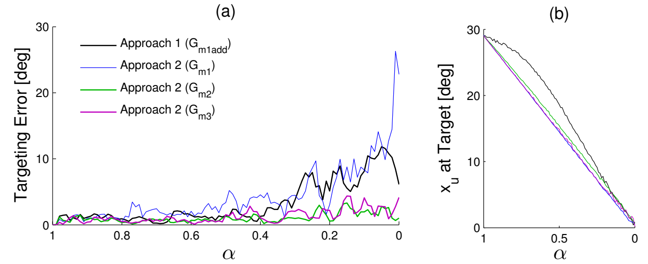

Fig. 6. Results of targeting task from one subject as α decreased from 1 to 0 in increments of 0.01. (a) For all cases, targeting error of the virtual finger increases as α nears 0. (b) Position of the user's finger when the virtual finger was at the target. Approach 2 resulted in a more linear reduction of movement, regardless of the model G_m.

A targeting task was completed by one subject to examine performance of the two approaches. A target at 30° and position of a virtual finger x_c were displayed on a screen (Fig. 5b). Each trial, at a fixed α, consisted of one movement toward the target from 0°. Fast motions were encouraged by providing feedback about whether the maximum virtual finger velocity fell within the desired range of 180–220 deg/s (140–180 deg/s for G_{m3}). Targeting error was measured as the angle between the target and x_c when the virtual finger velocity first dropped below 5 deg/s, prior to any corrective motions. Performance was consistently worse near isometric mode for Approach 1 (G_{m1add}) and Approach 2 (G_{m1}, G_{m2}, G_{m3}) (Fig. 6a). The user's finger position when the virtual finger reached the target shows how user movement was gradually reduced as α decreased from 1 to 0 (Fig. 6b).

IV. Discussion

The method of selecting and controlling system dynamics makes Approach 2 (Selectable dynamics) favorable over Approach 1 (Natural dynamics). In Fig. 6a, targeting error increased for all combinations of approach and model G_m as α approached 0, likely due to the lack of proprioceptive cues. This decline in performance could be minimized by altering the dynamics of the system, particularly for models G_{m2} and G_{m3} in Approach 2. It should be noted, however, that G_m parameter values were not chosen to ensure optimal performance given a specific form of model.

Movement of the user's finger is also affected by the value of α through the *Local Admittance Controller* (Fig. 6b). For Approach 2, the user's movement changes linearly with α, which is expected since x_u tracks αx_c. Alternatively, the effect of f_c on the user's motion in Approach 1 is not as straight forward, due to the $1 - \alpha$ term. This results in a nonlinear decrease in movement, which may be less favorable than a predictable, linear transition.

Disparity of the model G_m and natural G_n dynamics is another issue for Approach 1. The simplicity of this task prevented the accumulation of modeling errors, such that $\hat{x}_m$ was a fairly accurate estimate of x_u when $\alpha = 1$. However, model inaccuracies could be problematic for longer tasks, affecting both x_u and x_c, and would require re-zeroing.

The presented approaches for anisometric-isometric transition can be applied to HMIs for various biomedical purposes. An HMI capable of gradually transitioning between anisometric and isometric modes may help train people to use isometric interfaces, as it may be easier to adjust to a continuous rather than abrupt loss of proprioception. New movement rehabilitation paradigms can also be developed; isometric training has been shown to improve strength and abnormal joint torque coupling in stroke patients [12], and it would be desirable to have these improvements transfer to movement. Furthermore, a gradually transitioning HMI may allow for studies of human sensorimotor performance, particularly regarding the importance of proprioception, that may not have been previously feasible.

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