Adaptive Gravity and Joint Stiffness Compensation Methods for Force-Controlled Arm Supports

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***Abstract*—People with muscular weakness can benefit from arm supports that compensate the weight of their arms. Due to the disuse of the arms, passive joint stiffness increases and providing only gravity compensation becomes insufficient to support the arm function. Hence, joint stiffness compensation is also required, for which the use of active arm supports is essential. Force-based control interfaces are a solution for the operation of arm supports. A critical aspect of force-based interfaces, to properly detect the movement intention of the user, is the ability to distinguish the voluntary forces from any other force, such as gravity or joint stiffness forces. Model- and calibration-based strategies for the estimation of gravity and joint stiffness forces lack adaptability and are time consuming since they are measurement dependent. We propose two simple, effective and adaptive methods for the compensation of forces resulting from gravity and joint stiffness. The compensation methods are based on the estimation of the compensation force using a low-pass filter, and switching of control parameters using a finite state machine. The compensation methods were evaluated with an adult man suffering from Duchenne muscular dystrophy with very limited arm function. The results show that when gravity and joint stiffness forces were adaptively compensated the reachable workspace of the user was increased more than 50% compared to the workspace reached when only constant gravity compensation was provided.**

I. Introduction

People with muscular weakness can benefit from arm supports that compensate the weight of their arms [1], [2]. Due to the disuse of the arms, joint stiffness increases [3], [4] and users not only require gravity compensation but also assistance to overcome passive joint stiffness. In the case of muscular dystrophy the increase of joint stiffness is combined with the decrease of muscle force. Figure 1 shows the passive forces measured across the arm's workspace of an adult man with Duchenne muscular dystrophy (DMD). The maximum voluntary forces of the user were in the order of 1 N. Therefore, without stiffness compensation, the range of motion (ROM) of the user's arm is limited to the blue area.

Commercially available arm supports present three important limitations [5]: (I) they become insufficient at the last stages of the disease because they mainly provide vertical support, (II) are often highly stigmatizing due to their large dimensions (III) and, if active, they are controlled with manual interfaces, such as buttons or joysticks, which sacrifices the function of one hand to operate the device. In the Flextension A-Gear project [6] we want to make a step forward in the field of arm supports by developing a wearable and intuitively controlled arm support for people with severe muscular weakness.

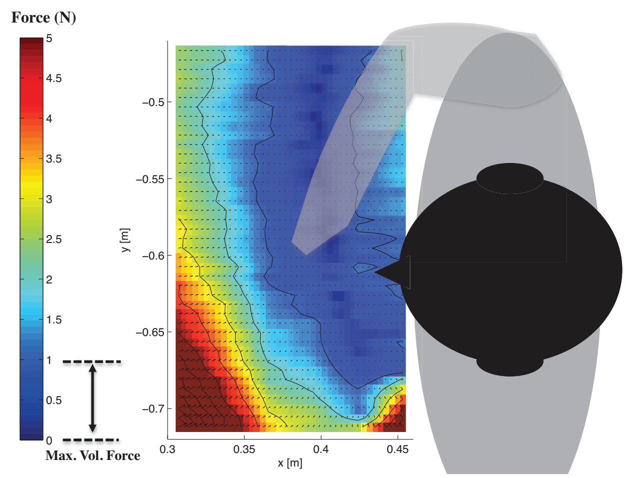

Fig. 1. Passive forces measured across the horizontal arm's workspace of an adult man with DMD. These forces were measured during a slow sweeping movement across the workspace with the arm attached to the setup shown in Fig. 2 and the subject relaxed. the measured data was then interpolated in x and y dimensions to generate the complete force field.

In previous studies [7], [8], force-based control interfaces for the operation of arm supports have shown to be a promising control strategy. A crucial aspect of force-based interfaces, to properly identify the user's movement intention, is the ability to accurately distinguish the voluntary forces from any other measured force. In this paper, we focus on the compensation of the two main continuous force disturbances that result from gravity and joint stiffness. These forces are challenging to estimate due to their non-linearity, time-variance and pose dependency [10], [11]. Additionally, voluntary forces of the arm are several orders of magnitude smaller than the gravity and joint stiffness forces of the arm [8]. Therefore, the required accuracy for the estimation of these forces should be kept below the maximum voluntary force to properly identify the intention of the user. Otherwise the arm support will be controlled by gravity and joint stiffness.

Few methods have been proposed to compensate gravity and joint stiffness forces. Ragonesi et al. [4] reported measurements of gravity and joint stiffness torques in patients with muscular weakness with the end goal of obtaining a biomechanical model of the arm that could be used for the

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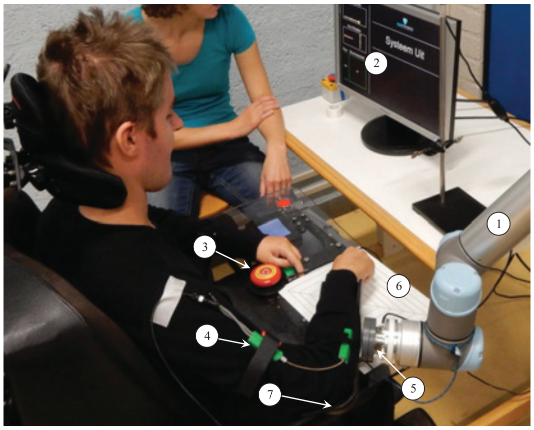


Fig. 2. An adult man with DMD with no arm function left using a force-controlled arm support and evaluating the adaptive gravity and joint stiffness compensation methods. 1: robotic manipulator, 2: computer screen for visual feedback, 3: emergency stop, 4: elbow angle sensor, 5: force/torque sensor, 6: square shapes used for the evaluation, 7: arm cup.

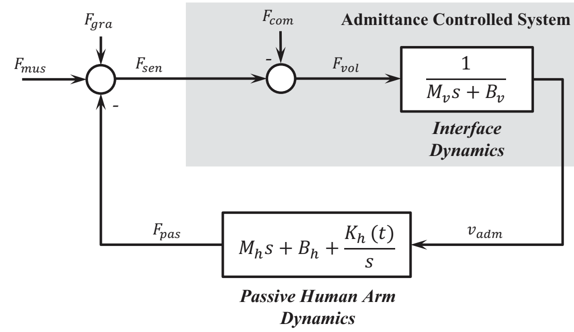


Fig. 3. Schematic overview of the interaction between the admittance controlled system (assistive device) and the human arm. The admittance controller haptically displays virtual interface dynamics to the user. Dynamics of the systems are described with linear transfer functions for clarity. The gravity force (F_{gra}), the muscular force of the user (F_{mus}) and the passive forces (F_{pas}) are all combined in the measured force (F_{sen}). The purpose of this work is to find the proper compensation force (F_{com}) to distinguish the voluntary forces of the user (F_{vol}) from joint stiffness and gravity forces.

control of an active version of the WREX arm support. Due to the high variability between the participants, the authors suggested subject-specific models as a strategy to optimize the estimation of gravity and joint stiffness forces. Another approach was presented by us in a previous study [8], in which we demonstrated that an adult man with DMD with no arm function left, could successfully operate an active elbow orthosis using a force-based control interface when gravity and joint stiffness were compensated. The gravitational and joint stiffness forces were estimated using a calibration procedure in which the orthosis together with the relaxed forearm of the participant slowly moved across the ROM of the elbow. A video showing the compensation force measurement can be found in [9] as additional file 4.

While model- and calibration-based compensation methods may work for the control of arm supports with multiple degrees of freedom (DOF), they are time-consuming and measurement dependent which limits their adaptability to the time-varying behavior of joint-stiffness.

In this paper, we present two methods: (I) trigger-based compensation and (II) gated control. They are simple to implement, effective and adaptive, allowing a responsive behavior of the arm support to the low-amplitude voluntary forces provided by the user. The methods were evaluated with an adult man suffering from DMD with very limited arm function using the setup shown in Fig 2.

II. BACKGROUD

A common force-based control strategy for haptic interfaces is admittance control. The paradigm in admittance control is that the user exerts a force on the device and the device responds with the corresponding motion according to the parameters of the admittance model. Our goal is to provide a compensation force (F_{com}) that will be added to the measured force (F_{sen}) to eliminate the effect of external force disturbances resulting from gravity, and internal force disturbances resulting from the human joint stiffness ($K_h(t)$; See Fig. 3). Note that the passive human dynamics have been simplified to a second order mass-spring-damper system. In this work we are not interested in the motion control loop (either controlling velocity or position) used in admittance control, and assume it to be ideal. Furthermore we assume the force and motion sensors to behave ideally and have infinite range and bandwidth, and no quantization.

The two proposed compensation methods analyze the interaction forces between the arm of the user and the arm support in the frequency domain. We performed a measurement of the interaction force with one healthy subject in three different conditions: (I) performing normal arm movements with a constant gravity compensation force of 30 N, (II) performing normal arm movements without compensation and (III) stationary with the same gravity compensation as in condition I. Figure 4 shows the frequency spectrum of the interaction forces, which can be separated in two frequency regions. Each of the bands corresponds to a different type of interaction force: from 0 Hz to 0.8 Hz the gravity, joint stiffness and the voluntary forces of the user, and above 0.8 Hz the high frequency disturbances. It is important to note that forces are found at 0 Hz only if they are constant. This is the case for stiffness and gravity forces in stationary situations or if the user generates a constant voluntary force. In dynamic situations the pose dependent stiffness and gravity forces will not be (only) found at 0 Hz as their amplitude will change.

From the frequency characteristics of the interaction force, it is reasonable to think that a way to remove the gravity and stiffness forces is to simply use a high-pass filter. However, this is not the case. If we assume that the force-controlled arm support is operated using admittance control and we add a first-order high-pass filter, the resulting transfer function will have the form of a mass-spring-damper system with passive physical equivalent [12] parameters for the damper B'_v and spring K'_v, which will depend on the filter cut-off frequency:

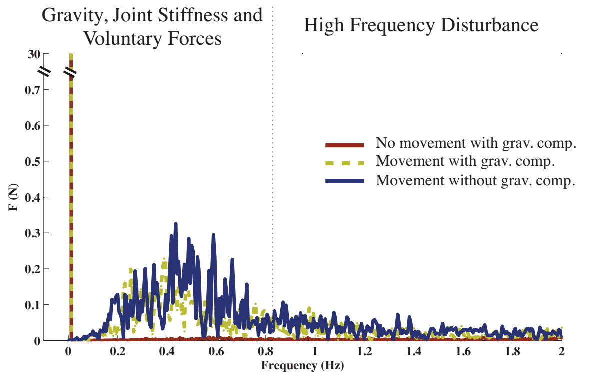


Fig. 4. Force spectrum of the interaction force between the user's arm and the arm support during arm movements with a constant compensation force of 30 N (dashed yellow line), without compensation (solid blue line) and with compensation and stationary (solid red line). Two separate frequency regions are identified. 0-0.8 Hz: forces resulting from gravity, joint stiffness and voluntary forces. Above 0.8 Hz: high frequency disturbance forces.

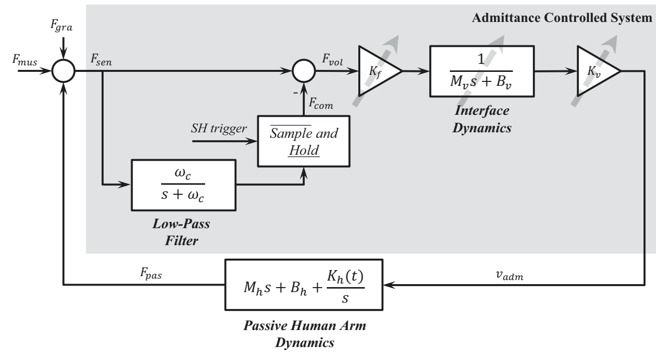


Fig. 5. Control diagram of the compensation methods. A Sample and Hold is triggered to sample a low-pass filtered version of the measured force when $SHtrigger = 1$, and hold that value when $SHtrigger = 0$. The F_{com} is the compensation force that is subtracted from the measured force F_{sen}. The force going into the interface dynamics F_{vol}, and the output velocity can be gated by K_f and K_v respectively.

$$H'_{id}(s) = H_{hpf}(s)H_{id}(s) = \frac{s}{s+\omega_c}\frac{1}{M_v s + B_v} = \frac{s}{M_v s^2 + (B_v + \omega_c M)s + \omega_c B_v} = \frac{s}{M_v s^2 + B'_v s + K'_v}. \quad (1)$$

Where s is the Laplace transform variable, M_v represents the virtual mass parameter, B_v the virtual damping parameter and ω_c is the cut-off frequency.

The resulting system dynamics (H'_{adm}) are not usable for an arm support, since we created a virtual parasitic spring $K'_v = \omega_c B_v$ that will be acting against the intended movement of the user. Filters can still be used to distinguish and quantify the constant forces resulting from gravity and joint stiffness in stationary situations. We will use this fact in the development of our new method.

III. Compensation Methods

Before explaining the devised methods, we explicitly state the most important assumptions made, considering the way the user generates forces on the interface:

- The user is able to relax and not produce any constant voluntary force during the estimation of the gravity and joint stiffness forces. This will prevent that the voluntary forces of the user are compensated.
- The user is able to produce a constant voluntary force against the joint stiffness and/or gravity forces in order to trigger the system. Required for the trigger-based compensation method when the button is not used.

The two proposed compensation methods rely on useful switching of model parameters, and by gating the force measurement and velocity of the device. This means we have a switching control system. Guaranteeing stability of switching dynamical systems, even from a stable to another stable system, is non-trivial [13]. Stability of our method is proved quickly due to the fact that the interface (by design of the mass-damper transfer function) and the human [14] both behave passively. Using the kinetic energy of the virtual model as a Lyapunov function (which holds for all switched versions of the dynamical system), it is directly proven that this system is asymptotically stable for all virtual damping and mass parameters B_v and M_v that are physically realistic, and therefore for all values of K_f (since it scales the parameters). Since setting $K_v = 0$ would stop the motion of the device, this makes that state of the system trivially stable.

The estimation of the gravity and joint stiffness forces is done using a first-order low-pass filter. Fig. 5 shows a general diagram of the control system. Our strategy is to provide intermittent control using a finite state machine. The sample and hold, the force and velocity gating gains (K_f, K_v) and the parameters of the interface dynamics change depending on the state of the finite state machine.

A. Trigger-based compensation

Fig. 6 shows the finite state machine of the trigger-based compensation method. The state machine can switch between two states:

State 0: Operation Mode
The arm support is controlled with an admittance model with low virtual mass M_v and damping B_v and is highly responsive to the interaction forces. As the subject generates forces, the device will move away from the starting point and the pose-dependent joint stiffness will start exerting a force. When the combination of gravity and joint stiffness forces equal the voluntary force of the user, the resultant force will be zero and the system will stop moving. At this moment, if the subject relaxes and stops generating a force, the gravity and joint stiffness force will pull him towards an equilibrium point. However, if the subject, instead of relaxing his arm, triggers the system, the state will change to *State 1*.

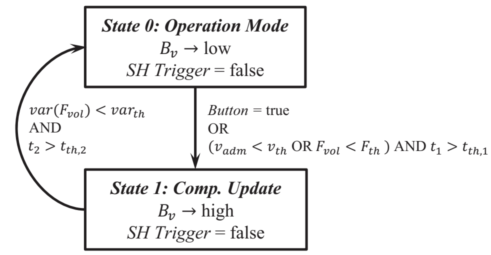


Fig. 6. Diagram of the finite state machine of the trigger-based compensation method.

State 1: Compensation Update
The damping parameter B_v of the interface dynamics is changed to a high value and the sample and hold will be continuously triggered to update the compensation force for a minimum predetermined amount of time, and until the variance of the voluntary force (F_{vol}) is lower than a predetermined threshold (F_{th}). It is required that just after the user triggers the system, the user stops generating constant voluntary forces to prevent that the system compensates the voluntary force of the user. The variance of the voluntary force ($var(F_{vol})$) is used to have an estimate on when the subject is relaxed. Once all the conditions are met the state will change to *State 0*.

We investigated two different ways of triggering the system: (I) using an external button that is operated with the hand or any other body part, and (II) detecting when a high-pass filtered version of the measured force or the velocity of the arm support remain close to zero for a certain amount of time. The idea of the second strategy is to avoid the sacrifice of a body part to press the button, and use instead a signal, which is implicitly related to the human interaction with the arm support.

B. Gated control

Figure 7 shows the finite state machine of the gated control method. The idea behind this method is that the user only needs to provide an input force for a short period of time, which may considerably reduce the effort compared to the method described in Sec. III-A. The state machine can switch between four states:

State 0: Gate Closed
The force and velocity gate gains K_f and K_v are set equal to zero. Therefore, the arm support does not move. When the user generates a voluntary force (F_{vol}) above a predetermined threshold (F_{th}), the state changes to *State 1*.

State 1: Force Gate Open
The force gate gain K_f will be equal to one for a predetermined amount of time $t_{th,1}$. Once this time has elapsed, the state changes to *State 2*.

State 2: Velocity Gate Open
The force gate gain K_f will be equal to zero again and the velocity gate gain K_v will be equal to one. The arm support will move proportionally to the input force provided in *State 1* and the parameters of the interface dynamics. When the velocity (v_{adm}) drops below a predetermined threshold (v_{th}, which should be close to zero), and the variance of the voluntary force ($var(F_{vol})$) is lower than a predetermined threshold (var_{th}) the state changes to *State 3*.

State 3: Compensation Update
This state will trigger the sample and hold to update the compensation force. After another predetermined period of time $t_{th,2}$ the state changes back to *State 0*.

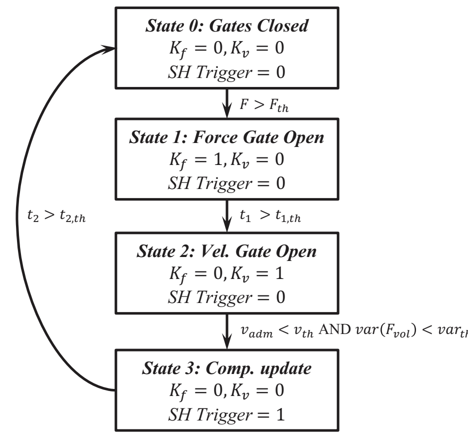


Fig. 7. Diagram of the finite state machine of the gated control.

IV. Evaluation

The evaluation of the proposed gravity and joint stiffness compensation methods has been carried out with a research setup that consists of a 6 DOF manipulator (UR5, Universal Robots A/S, Odense, Denmark), 6 DOF force/torque sensor (mini45, ATI Industrial Automation, Apex, USA), and a plastic arm cup from the Darwing arm support (Focal Meditech BV, Tilburg, The Netherlands) with a custom-made wrist support. From pilot trials with our setup we found that a cut-off frequency of 0.5 Hz for the low-pass filter used to estimate the compensation force, provided a fair trade-off between speed and estimation accuracy. We performed two types of evaluations: proof-of-concept evaluations and end-user-based evaluations.

A. Proof-Of-Concept

For the proof-of-concept evaluations, we used a rubber band to simulate the effect of the human joint stiffness. The band was attached between the arm cup and a fixed point (Fig. 8a). During this test we performed one-dimensional horizontal movements. Figures 8b and 8c show an illustrative time course of the force and velocity signals during the different states of the trigger-based compensation and the gated control method. For the sake of clarity the force signals were smoothed with a low-pass filter using the *filtfilt* function of Matlab.

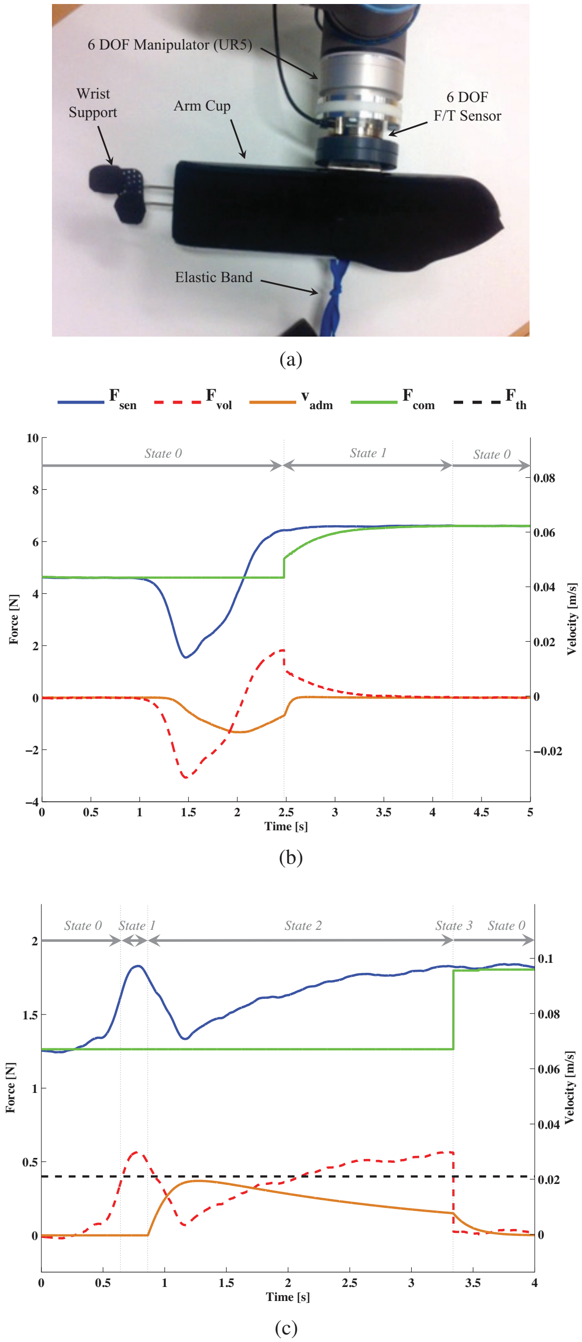


Fig. 8. a) Setup used to evaluate the compensation strategies. The rubber band was used to simulate the effect of the human joint stiffness during the proof-of-concept evaluation. b) Illustrative functioning of trigger-based compensation using a button. b) Illustrative functioning of the gated control. The vertical dashed grey lines indicate the change of state.

B. End-User Evaluation

For the end-user evaluation, we asked a 23-year-old man suffering from DMD with very limited arm function to perform two-dimensional horizontal movements and one-dimensional vertical movements (Fig. 2). Note that while the subject has no arm function left, he can still produce distinguishable forces, which are not functional without adequate support. The task was to reach the maximum workspace possible within two minutes. The Medical Ethics Committee of the Radboud University Nijmegen Medical Centre approved the study design, protocols and procedures, and informed consent was obtained from the participant. The maximum voluntary force of the participant force was approximately 1 N in the horizontal plane and 0.5 N in the vertical plane. The participant had visual feedback of the measured forces and the states of the state machine. Before starting the actual test, the arm of the participant attached to the robotic manipulator was actively moved by a therapist across the workspace to define the safety position-boundaries.

Figure 9 shows the two-dimensional workspace in the horizontal plane and the one-dimensional workspace in the vertical direction that the subject was able to reach with the proposed compensation methods and with the commonly used constant gravity compensation. Relative to the area delimited by the safety position-boundaries (black dashed line in Fig. 9), the reachable workspace was 79%, 71% and 21.5% when using the gated control, the trigger-based compensation and the constant gravity compensation respectively. Note that the constant gravity compensation in the two-dimensional horizontal movements does not have any effect. Regarding the vertical movements, the participant was able to reach the height limit with both adaptive compensation methods and 55% of the height limit with the constant gravity compensation.

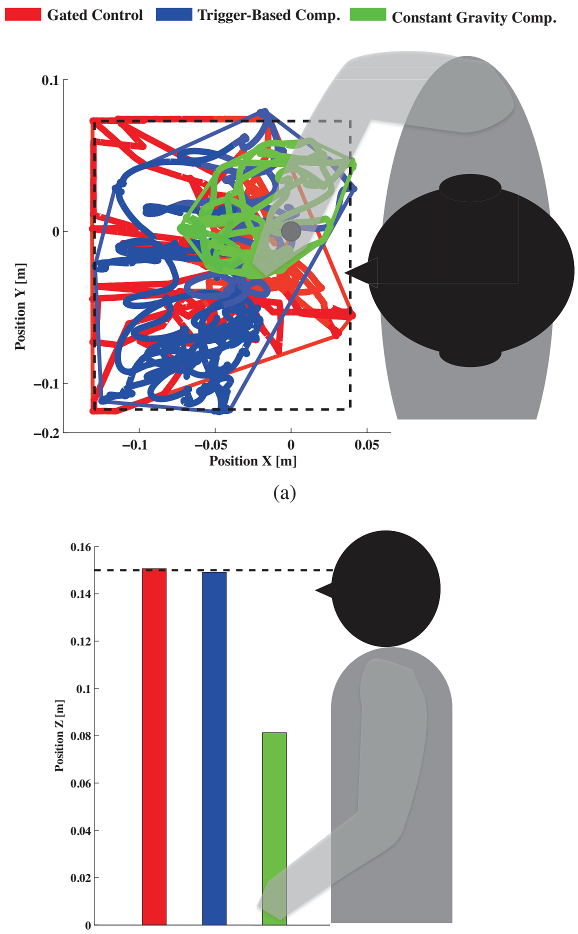
V. Discussion and Conclusions

This paper presents two adaptive methods to estimate and compensate the non-linear, pose-dependent and time-varying forces resulting from gravity and joint stiffness. Contrary to model- and calibration-based compensation methods, the methods we propose are not measurement dependent, which simplifies their implementation, and can adapt to the time-varying behavior of joint stiffness.

From the evaluations, we concluded that both the trigger-based compensation method and the gated control can accurately compensate the gravity and joint stiffness forces. Thus, allowing responsive behavior of the arm support to the low-amplitude voluntary forces provided by the user. The horizontal and vertical workspace of the participant was greatly increased when adaptive gravity and joint stiffness compensation was provided. When using only constant gravity compensation the workspace was limited and the subject experienced high levels of fatigue.

The compensation strategies proposed in this paper require some training effort from the user to learn to relax his arm during the compensation force update. We found that after a short training (i.e. 5 minutes) the participant was able to relax his arm during the update of the compensation force. Taking into account the high adaptability of humans, we believe this effort is minimal compared to the functional benefits that users gain using these compensation methods. Future research will investigate further the practical usability of the compensation methods.

While the trigger-based compensation provided more freedom of movement compared to the gated control, because in its operational mode the system is admittance



(a)

(b)

Fig. 9. Workspace reached by the participant in 2D horizontal (a) and 1D vertical (b) movements using the gated control (red), the trigger-based compensation (blue) and constant gravity compensation (green). The black dashed line indicates the safety position-boundaries implemented on the robotic manipulator, and the black dot indicates the initial position of the hand. The poligon that delimits the 2D workspaces have been calculated using the convex hull function in Matlab ($convhull$).

controlled, the participant experienced a higher level of effort. The participant especially noticed the increase of effort when using the force or the velocity signal to trigger the system, since he needed to produce a constant voluntary force against gravity and joint stiffness forces for a short amount of time to trigger the system. Additionally, if the user has very limited force and high joint stiffness, he will need to update the compensation frequently, which will result in a slow and intermittent movements. In this respect, the gated control presents the advantage that since the force-loop is open during movement, the velocity (v_{adm}) can be amplified as much as needed without causing any stability issues. This will result in larger and less intermittent displacements compared to the trigger-based compensation. However, due to the open-loop behavior of the gated control method the user needs to learn the interface dynamics to estimate how much input force is required to reach a desired position.

Considering the aforementioned capabilities and limitations of each method, we foresee that the gated control might be more suitable for users with voluntary forces below or similar to the joint stiffness forces, and the trigger-based compensation more suitable for users with voluntary forces above the joint stiffness forces.

Future work will include the evaluation of the proposed methods with several participants during discrete position-tracking tasks in horizontal and vertical movements. Furthermore, we plan to develop a calibration procedure to compensate for the force asymmetry and the force direction errors of the users, which were already noticeable during the preliminary tests.

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