Case Studies of Musculoskeletal-Simulation-Based Rehabilitation Program Evaluation

Leng-Feng Lee, Madusudanan S. Narayanan, Srikanth Kannan,
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***Abstract*—Variability in motor rehabilitation program outcomes can be attributed not only to individual components (human patient/rehabilitation equipment) but also to their system-level interactions. Thus, effective deployment of a rehabilitation program depends upon: 1) suitable therapist selection of user–device ergonomics; 2) adjustable device settings; and 3) exercise regimen parameters; to achieve desired system-level motor performance. In this paper, we discuss aspects of creation of a virtual design environment, leveraging tools from musculoskeletal analysis, optimization, and simulation-based design, to permit therapists to rapidly evaluate and systematically customize rehabilitation programs. Specifically, this framework is intended to facilitate 1) parametric study of ergonomic/device/regimen settings on musculoskeletal performance; 2) use of design tools such as optimization for decision support in arriving at the best program; and 3) scaffolded examination of linkage between form and function by iterative what–if type of analyses. We use two case studies (bicep-curling and motor rehabilitative driving) to highlight benefits of such simulation-based rehabilitation program evaluation.**

***Index Terms*—Computational musculoskeletal analysis, rehabilitation, simulation-based optimization.**

I. INTRODUCTION

A growing number of people suffer from diminished motor capabilities, due to disease (e.g., muscular dystrophy and stroke), aging, or simply disuse. There is considerable evidence that links functional recovery to the duration, frequency, regularity, and intensity of the rehabilitation therapy [1], [2]. Physical rehabilitation entails performance of structured repetitive motor rehabilitative physical exercises, typically with specialized equipment, in order to rebuild strength/functional capacity.

Many factors contribute to the variability witnessed in the therapeutic outcomes of motor rehabilitation programs [3]. At the component level, there is innate variability of performance and function across individuals in a population (due to sex/age/race as well as progress of disease/recovery). The availability of exercise equipment and selection of rehabilitation regimen also creates variability. Enhanced therapeutic outcomes can be realized by allowing a therapist to: 1) control the user–device ergonomic layout; 2) adjust the device parameters; and 3) tailor the exercise regimen. However, system-level interactions between patients and rehabilitation equipment make it difficult for therapists to select the "best" set of options/parameters to realize desired therapeutic outcomes.

In this paper, we examine the application of Virtual Prototyping (VP) [4], [5] methodology to *study*, *evaluate*, and *refine* interactions of a patient with the rehabilitation equipment/regimen. VP refers to functional simulation, quantitative performance analysis, and iterative refinement of products and processes in a virtual environment. The principal benefits accrue from the capacity for rapid quantitative and computational exploration of numerous "what–if" design scenarios at relatively low cost. Specifically, in this paper, we will focus on developing a "computational design tool" for therapists to systematically: 1) study effects of variability; 2) determine the "best" geometries and regimen; and 3) examine the linkage between form and function using "virtual experimentation." Two case studies of bicep-curling [6] and motor rehabilitative driving [7], [8], help to highlight various aspects of the simulation-based rehabilitation program evaluation.

The rest of this paper is organized as follows. In Section II, we discuss some of the critical challenges involved in creating the proposed framework. Section III presents an overview of the various individual modules that come together to form the Virtual Design Environment (VDE). The bicep curl study in Section IV develops the use of parametric sweeps to study form–function relationships. Section V examines parameter selection/customization of a haptic virtual driving environment (hVDE) to facilitate focused motor rehabilitation. Section VI concludes with a discussion of avenues for future work.

II. CRITICAL CHALLENGES

The overall rehabilitation program refinement can be systematized by treatment in the form of a "design problem" [9]. In such a setting, design decisions can be made by systematic generation of candidate designs, evaluation by quantitative criteria, and, finally, elimination of undesirable candidate designs. VP tools in engineering have capitalized on setting up and solving such problems by coupling parametric models with functional simulation tools and optimization methods [4]. In particular, the availability of low-cost PC-based parametric simulation and analysis tools, and integrating multiple functionalities into a unified environment, has favored the adoption and rapid proliferation of the "computational/virtual exploration" approach. Nevertheless, there remain significant obstacles to successful implementation as a rehabilitation program design tool for therapists.

On one hand, the effectiveness is limited by the extent of capture of the underlying physics, the modeling and analysis fidelities, and ultimately computational power. In developing rehabilitation regimen, effective simulation of interactions between the user, the device, and the environment becomes critical. Varying levels of such simulations are possible, e.g., several digital human modeling tools such as Jack allow kinematic modeling of human–device–environment interactions. The ability to monitor internal human variables, such as joint angles and torques, from the virtual avatar formed the basis of a user-customized development of human-worn products [4], [5]. The recent availability of professional-grade computational musculoskeletal analysis tools [10]–[14] now facilitates virtual simulation-based analysis of detailed and biomechanically accurate models. We capitalize on this "insight" into the internal human variables, including muscle and joint motions, and forces, in our work (details are provided in Section III-A).

On the other hand, there is a critical need for structuring and systematizing the user-interactions of noncomputational users with high fidelity VPs. Many levels of scaffolding are usually required to: 1) provide varying levels of task- and context-dependent assistance and 2) allow noncomputational users to build experience with the computational/virtual exploration paradigm for skill improvement or process and content understanding [15], [16]. Thus, a constrained/scaffolded interaction framework is key to tapping the power of Virtual Prototyping by noncomputational users.

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III. IMPLEMENTATION

The Virtual Design Environment was designed to help noncomputational users (such as rehabilitation therapists and, more generally, health-care professionals) to interactively access and understand functional performance aspects of the human musculoskeletal system. The developed interactive user-friendly scaffolded interface unlocks the power of the computational musculoskeletal analysis engine to perform virtual experimentation.

A. Computational Musculoskeletal Analysis Tools

Many computational tools have been developed for kinematic and dynamic analyses of vertebrate musculoskeletal systems, building on an articulated multibody systems (AMBS) framework [14]. Constrained musculoskeletal system-level computational models can be constructed modularly by placing physiologic and behavioral constraints on anatomical components (e.g., bone, muscle, and tendon). Such musculoskeletal analysis tools allow monitoring of internal human variables - a wide variety of biologically relevant data (from lengths, forces, reactions of muscles/tendons/joints, to metabolic power consumption, and mechanical work) can be accessed. Alternatively, other higher level abstracted performance measures may be developed, allowing a therapist to directly monitor the effects of a regimen on target muscle groups and allow grasping of the functional relationship of muscles.

Examples include both commercial tools such as LifeMod [11], SIMM [12], and AnyBody [14], as well as the more recent open source tools such as OpenSim [10], [13]. Among these, the AnyBody modeling system offered a convenient tool for modeling and analyzing various vertebrate musculoskeletal systems. The AnyBody musculoskeletal model is built up as a constrained articulated multibody system with rigid skeletal bones overlaid with multiple muscles that serve to both constrain and actuate the system. The governing equations can be obtained as the constrained dynamic equations of this articulated multibody system. However, the significant actuation redundancy creates indeterminacy for resolving muscle–actuator forces via inverse dynamic analyses. The indeterminacy in muscle force distribution is resolved using an optimization approach. In AnyBody [17], redundancy resolution takes the form of minimization of the maximal muscle activity subject to equality constraints (multibody dynamic equations) and nonnegative muscle force constraints

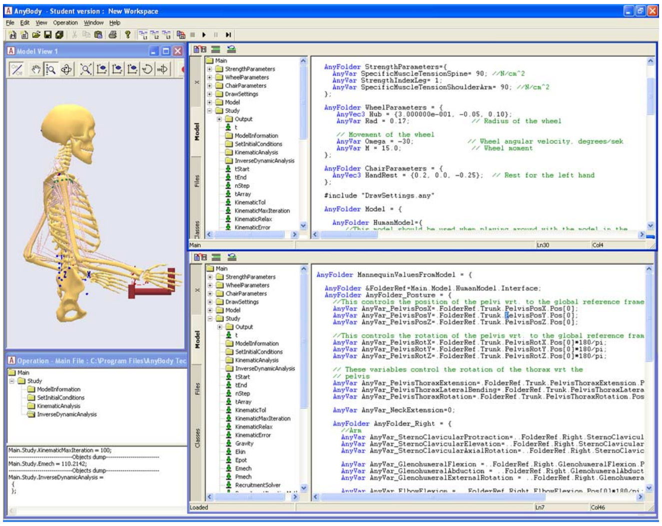
$$\min_{\mathbf{f}} G\left(\mathbf{f}_{\text{muscle}}\right) = \max\left(\frac{f_{\text{muscle},i}}{N_i}\right), \qquad i = 1, \ldots, n_{\text{muscle}} \tag{1}$$

$$\text{Subject to}: \; \mathbf{Cf} = \mathbf{r} \tag{2}$$

$$f_{\text{muscle},i} \geq 0. \tag{3}$$

Many contemporary studies [18]–[20] have examined the validation of Anybody dynamic simulations in various application contexts. The ability to resolve muscle activities/forces (beyond the more traditional joint forces and moments), and relate these directly to electromyography (EMG) data was also extremely attractive [18], [19].

However, as seen in Fig. 1 such tools remain very inaccessible to a noncomputational user due to the lack of both programming knowledge and numerical-analysis background to take advantage of the "computational testing paradigm." This is the shortcoming that we seek to address within this paper. We exploit the convenient scripting interface offered by AnyBody to facilitate access to the underlying computational engine from external programs, as discussed next.



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------------------------------Objects dump------------------------------
Main.Study.Emech = 110.2142;
------------------------------Objects dump------------------------------
Main.Study.InverseDynamicAnalysis =
 {
 };
```

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AnyFolder StrengthParameters={
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  AnyVar StrengthIndexLeg= 1;
  AnyVar SpecificMuscleTensionShoulderArm= 90; //N/cm^2
};

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   AnyVar Rad = 0.17;                // Radius of the wheel

   // Movement of the wheel
   AnyVar Omega = -30;              // Wheel angular velocity, degrees/sek
   AnyVar M = 15.0;                  // Wheel moment
};

AnyFolder ChairParameters = {
  AnyVec3 HandRest = {0.2, 0.0, -0.25};  // Rest for the left hand
};

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  AnyFolder HumanModel={
     //This model should be used when playing around with the model in the
```

```
AnyFolder MannequinValuesFromModel = {

  AnyFolder &FolderRef=Main.Model.HumanModel.Interface;
  AnyFolder AnyFolder_Posture = {
    //This controls the position of the pelvi wrt. to the global reference frame
    AnyVar AnyVar_PelvisPosX=.FolderRef.Trunk.PelvisPosX.Pos[0];
    AnyVar AnyVar_PelvisPosY=.FolderRef.Trunk.PelvisPosY.Pos[0];
    AnyVar AnyVar_PelvisPosZ=.FolderRef.Trunk.PelvisPosZ.Pos[0];

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    AnyVar AnyVar_PelvisRotY=.FolderRef.Trunk.PelvisRotY.Pos[0]*180/pi;
    AnyVar AnyVar_PelvisRotZ=.FolderRef.Trunk.PelvisRotZ.Pos[0]*180/pi;

    // These variables control the rotation of the thorax wrt the
    // pelvis
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    AnyVar AnyVar_PelvisThoraxLateralBending=.FolderRef.Trunk.PelvisThoraxLatera
    AnyVar AnyVar_PelvisThoraxRotation=.FolderRef.Trunk.PelvisThoraxRotation.Pos

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    AnyFolder AnyFolder_Right = {
      //Arm
      AnyVar AnyVar_SternoClavicularProtraction=..FolderRef.Right.SternoClavicul
      AnyVar AnyVar_SternoClavicularElevation=..FolderRef.Right.SternoClavicular
      AnyVar AnyVar_SternoClavicularAxialRotation=..FolderRef.Right.SternoClavic

      AnyVar AnyVar_GlenohumeralFlexion =..FolderRef.Right.GlenohumeralFlexion.P
      AnyVar AnyVar_GlenohumeralAbduction = ..FolderRef.Right.GlenohumeralAbduct
      AnyVar AnyVar_GlenohumeralExternalRotation = ..FolderRef.Right.Glenohumera

      AnyVar AnyVar_ElbowFlexion = ..FolderRef.Right.ElbowFlexion.Pos[0]*180/pi;
```

Fig. 1. Specialized programming knowledge required to use musculoskeletal analysis software.

B. Scaffolded Graphical User Interface (GUI)

Parametric designs simplify the process of systematic generation of choices especially in a computer-based implementation. Parametric models of the human patient are extracted from libraries (and can potentially be customized to reflect the specific patient characteristics). Similarly, a model of the rehabilitation device can be created and customized within the same framework. The model of the user and the model of the device can thus be cosimulated, and the obtained results can be used for refinement.

However, appropriate selection of design variables (that are both biomechanically relevant and are of significance to the user) poses challenges. For simplicity, we classify the multiple sets of properties under user control into three broad categories: 1) *geometric parameters* such as limb lengths and joint angles; 2) *device parameters*, such as adjustable resistance, spring constants, and damping ratios; or 3) *regimen parameters,* such as joint velocities, frequency, and amplitude of a desired motion. These design variables are used to systematically explore the space of feasible alternatives.

A GUI was also developed to facilitate structured user interaction with AnyBody settings (e.g., using radio buttons and sliders) allowing performance of parametric studies by manually varying the appropriate design variables. However, as the numbers of parameters grows, it can be very difficult to interactively vary all the parameters. Thus, decision support tools such as optimization (and sensitivity analysis) were also incorporated to aid the process of finding the "best" regimen. The optimization process, data manipulation, and interfacing to Anybody are handled using MATLAB, and the results of the optimization are displayed back within the GUI (as shown in Fig. 2).

IV. CASE STUDY I: PARAMETRIC BICEP CURL STUDY

The parametric bicep curl study on the upper arm/shoulder musculoskeletal model was created to allow healthcare students [including occupational therapy (OT)/physical therapy (PT)] in a gross anatomy class to systematically study relationships between form and function [6]. Pedagogically, this example is highly relevant in its ability to illustrate system-level effects of various components. More importantly, we were able to extend it easily to explore the effects of variability of *geometry*, *dynamics*, and *regimen* on *musculoskeletal performance*.

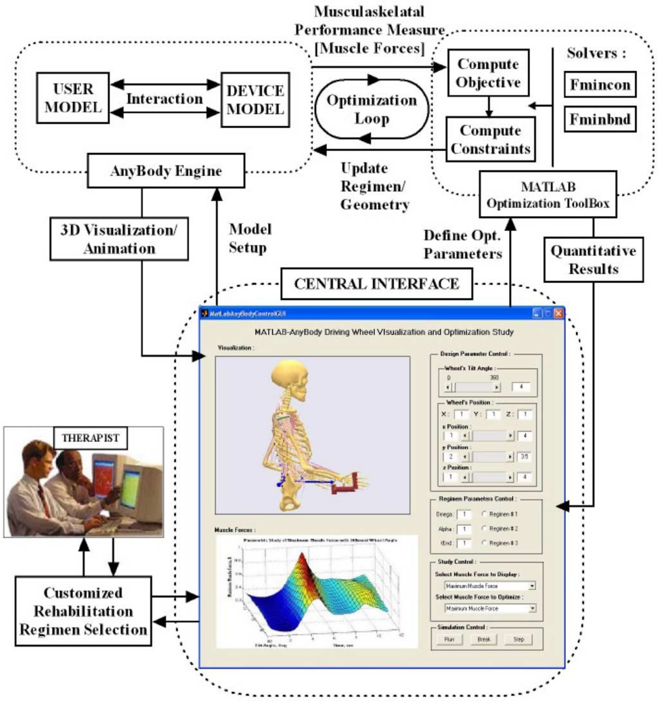


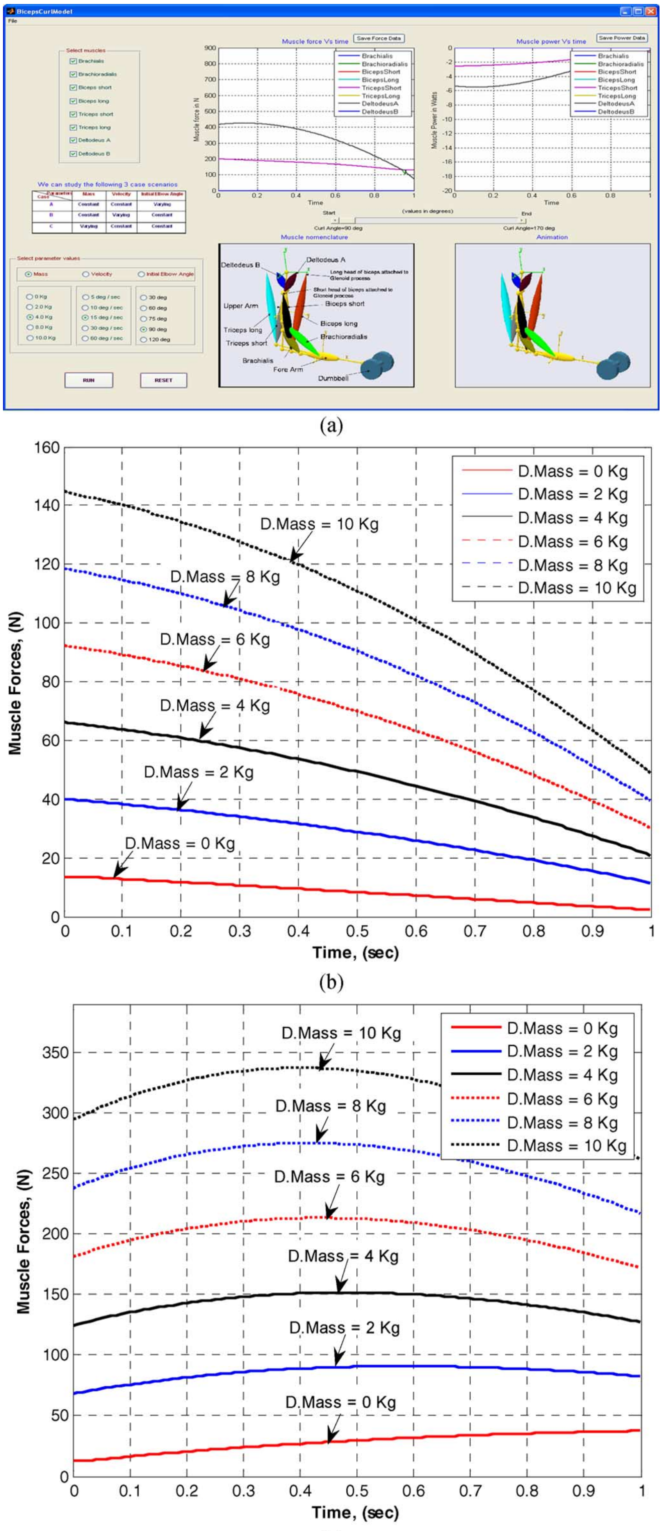
Fig. 2. Virtual Design Environment: The front end MATLAB based Graphical User Interface allows the therapist to examine the effects of different regimen and determines the ‘best’ regimen based on user’s geometric information. The AnyBody engine computes muscle forces, while the optimization routine is handled using MATLAB’s optimization toolbox.

The VDE permitted a systematic and scaffolded interaction by these students with state-of-the-art musculoskeletal analysis tool. Specifically, they could study variability of bicep force performance due to parameter variations in 1) initial elbow joint position (ergonomic); 2) mass of the dumbbell (device); and 3) elbow-joint velocity (regimen). Fig. 3(b) and (c) depicts the variation in bicep short and bicep long muscles for a parametric variation of dumbbell mass between 0 and 10 kg while keeping the initial elbow angle at 90° and elbow velocity at 45 rad/s. In addition to the quantitative results, such virtual experimentation can help to develop the students’ intuition about musculoskeletal performance trends.

V. CASE STUDY II: MOTOR REHABILITATIVE DRIVING STUDY

We also examined aspects of variability on rehabilitation within a motor-rehabilitative VDE [7]. This VDE was developed by integrating a commercial-off-the-shelf (COTS) force-feedback steering wheel with parameterized rehabilitation therapies to serve as a home-based inexpensive personal movement trainer [as shown in Fig. 4(a)]. Users perform structured rehabilitation exercises in the form of driving tasks along prescribed parametric paths while holding the steering wheel with one or both hands.

For computational efficiency, we restricted the human model to the upper body (bone–tendon–muscle) model from the pelvis up, obtained from the human repository [14]. Additional rehabilitation device components (such as the steering wheel) were added to this model, and the scaffolded GUI was set up to facilitate the therapist access (as shown in Fig. 2). This allowed a therapist to quantitatively examine system-level musculoskeletal interactions using a combination of parametric sweeps and optimization studies, as discussed next.



(a)

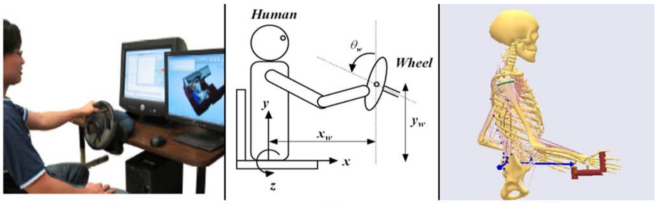
(b)

(c)

Fig. 3. Parametric Bicep Curl Study on a simplified Upper-Arm/Shoulder Musculoskeletal Model with the (a) Graphical User-Interface; and muscle force profiles for both (b) Biceps-short and (c) Biceps-long muscles.

A. *Parametric Studies*

The ergonomics of patient–steering-wheel interactions are governed by the spatial location of the center (x_w, y_w, z_w), radius (R_w), and tilt



(a) (b) (c)

Fig. 4. (a) Actual setup being modeled and studied. (b) Side view of the user and driving wheel (rehabilitation device) arrangement in Case Study II. (c) Corresponding side view of the human musculoskeletal model with the rehabilitation device modeled in AnyBody Modeling System.

angle (θ_w)of the steering wheel with respect to the global frame [as shown in Fig. 4(b)]. Parametric studies were performed for various combinations of selected parameters within the reachable region of the user. Here, we present only studies related to effects of selection of x_w and θ_w individually on overall system muscle forces. From Fig. 5(a), it is apparent that as the wheel is moved away from the user, the peak overall muscle force drops from 1.41 N ($x_w = 0.15$ m) to 0.9 N ($x_w = 0.41$ m). From Fig. 5(b), we see that the peak of the overall muscle force decreases from 0.92 to 0.74 N as tilt angle θ_w increases from 0° to 60°.

B. Optimization Study

Alternately, an optimization study can be created to help therapists determine the best possible placement of the device for specific objective of reducing peak muscle activity. Using the same two design variables as in the parametric study before, i.e., the tilt angle (θ_w) and wheel's *x*-position (x_w), the optimization problem can be written as

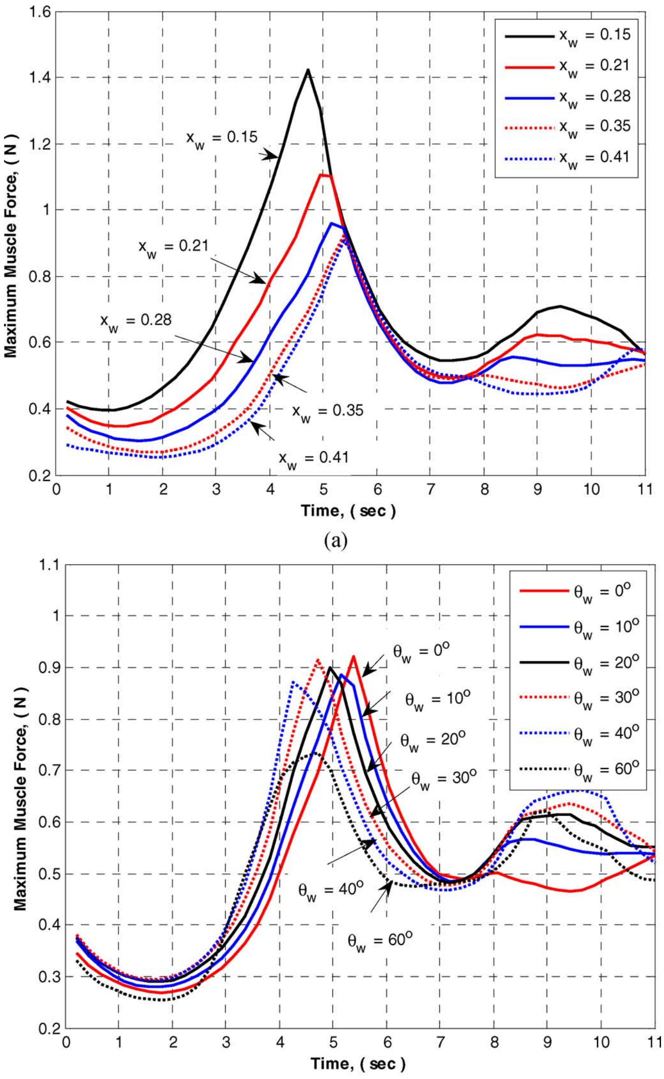
$$\operatorname*{Min}_{x_w, \theta_w} \quad f(x_w, \theta_w) \tag{4}$$

$$s.t: g_1: 0.15 \le x_w \le 0.26$$
$$g_2: 0^\circ \le \theta_w \le 60^\circ \tag{5}$$

For this relatively small problem, the objective function can be explicitly visualized by sweeping over the range of design parameters. Fig. 6 depicts the contour plots of the function space on a grid with 49 data points in the θ_w direction and 13 data points at the x_w direction. Despite the coarseness of the grid, this contour plot gives us a good estimate for the location of the optimum. In general, the muscle forces fluctuation of the overall system can be minimized by placing the steering wheel away from the user with a higher tilt angle. For larger problems with more design variables, such a visualization-based solution process of finding the "best" solution may not be viable. Numerical optimization techniques in MATLAB were employed to help with such design selection and to pave the way for a decision support tool for therapists.

VI. SUMMARY

In this paper, we presented the architecture and implementation of a VDE that facilitates the rapid refinement of rehabilitation program in the presence of the ergonomic-, device-, and regimen-variability. The architecture emphasizes scaffolded parametric interaction with detailed virtual human musculoskeletal models. Hypotheses-testing with virtual what–if analyses was illustrated in two case studies. The framework is intended to enable spectrum of end users (from healthcare students to clinicians) to explore the interconnections between form and function in both a quantitative and qualitative computational setting.



(a)

(b)

Fig. 5. Parametric study of the overall muscle forces. (a) With 0° tilt angle, x_w varied from 0.15 to 0.41 m. (b) With wheel centered at (0.25, −0.1, and 0.25 m), tilt angle θ_w varied from 0° to 60°.

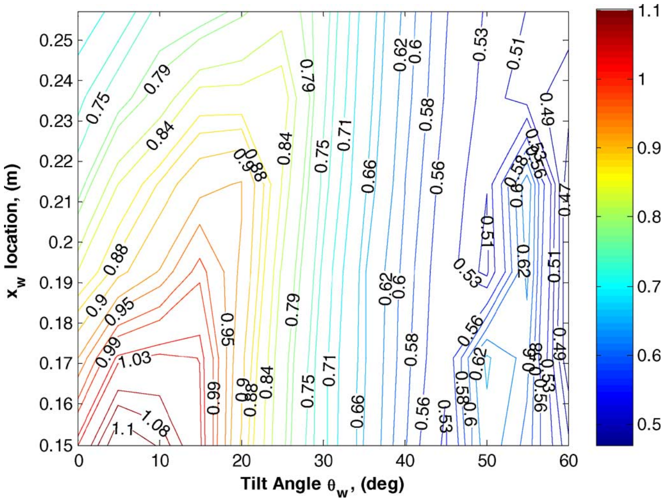


Fig. 6. Peak muscle activity depends on θ_w and x_w.

The basic ideas in this paper - quantitative study of user/device variability, systematic device parameter selection, and user/device interaction customization - can easily be extended to a broad class of rehabilitation programs. However, much work needs to be done in terms of 1) creating a more seamless VDE interface for therapists; 2) developing quantitative performance measures that are well balanced computationally and are of significance/relevance to therapists; 3) applying the framework to a wider range of settings; and 4) deploying this in realistic teaching and practice settings. We are actively pursuing all these aspects in our current work.

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Interpersonal Synchronization of Body Motion and the Walk-Mate Walking Support Robot

Yoshihiro Miyake

***Abstract*—Everyone has probably experienced the phenomenon where their footsteps unconsciously synchronize with their partner while walking together. This interpersonal synchronization of body motion has been widely observed and is significant in the context of social psychology. However, the mechanism of this embodied cooperation still remains obscure and has not been substantially developed as an engineering application. In this study, by assuming "mutual entrainment" as an interpersonal synchronization mechanism, we establish a new cooperative walking system between a walking human and a walking robot (an agent as a virtual robot). In this system, rhythmic sounds corresponding to the timing of footsteps are exchanged between them on the basis of our previous studies. As a result, it was demonstrated that the two walking rhythms adapt mutually after the start of interaction, and stable synchronization is generated automatically. This global entrained state exhibits dynamic stability with small fluctuation in the walking period. Applying this method to walking support for Parkinson's disease and hemiplegia patients, its effectiveness in stabilizing the walking of the patient was shown. These results indicate the importance of interpersonal mutual entrainment of rhythmic motion for walking support, and new human–robot interaction technologies are expected as an extension of this framework.**

***Index Terms*—Human–robot interaction, mutual entrainment, walking support, Walk-Mate.**

I. INTRODUCTION

Everyone has probably experienced the phenomenon where their footsteps unconsciously synchronize with their partner while walking together. This interpersonal synchronization of body motion has been widely observed and is significant in the context of social psychology [1]–[3] and developmental psychology [4]–[6]. However, the mechanism for this type of embodied cooperation still remains obscure and has not been substantially developed as an engineering application. This study therefore hypothesizes "mutual entrainment" [7]–[9] as a synchronization mechanism, and we establish a new cooperative walking system between a walking human and a walking robot (an agent as a virtual robot; Walk-Mate).

Automatic interpersonal synchronization of body motion is widely observed in social communication and collaboration. Condon and Sander, for example, analyzed the onset timing of an infant's body motion with his mother's utterances and reported an interpersonal synchronization between them [2]. Matarazzo *et al.* analyzed the conversational process between an interviewer and an interviewee and clarified a similar phenomenon in which the utterance duration, utterance speed, and switching pause are tuned among speakers [1]. Our group has already reported a similar synchronization phenomenon between walking rhythms during interpersonal cooperative walking [10].

This type of automatic synchronization can be considered to be an effect of dynamic interaction between nonlinear oscillators. In the cooperative walking mechanism, the interaction between neural rhythms generated by a central pattern generator (CPG) [11] is considered to be

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