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TITLE: Determining the Marker Configuration and Modeling Technique to Optimize the Biomechanical Analysis of Running-Specific Prostheses

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The purpose of this study is to develop and validate a model with optimal set-up of reflective markers, producing minimal errors in inverse dynamics calculations. The Statement of Work for this project indicated two specific aims. Specific Aim 1 proposed to develop and validate a model with unique optimal marker placements for specific running prosthesis designs. The proposed timeline indicated that preparation for the experimental setting and formulation of the program for data analysis would occur during Months 1-8. These milestones were reached on schedule. During Months 8-16, we proposed to complete MTS testing, begin validating the general model, and begin analyzing the MTS data to determine the final marker model for each running-specific prosthesis. We are currently in Month 13 of the project since its formal approval on August 1, 2009, and we are on schedule of the proposed timeline for these milestones. The general analysis model is in the process of validation and raw experimental data has begun being analyzed for the final marker model for each prosthesis design. Upon completion of Specific Aim 1 goals, we will complete goals set for Specific Aim 2, to determine the resultant optimal marker placement for all tested running prosthetic designs.

15. SUBJECT TERMS
Force, Moment, Inverse Dynamics, Biomechanics, Model, Running, Prosthesis

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Introduction

While running has been shown to reduce disease risks and promote a generally healthy lifestyle in uninjured people, very little running-specific research is available pertaining to the amputee population. The little existing amputee running literature primarily involves running with prostheses designed for every day wear, which are typically prescribed and aligned to perform optimally during standing and walking. Further, these studies have used biomechanical models designed for the intact limb to estimate joint kinetics (forces and moments) using an inverse dynamics approach. This approach estimates distal joint kinetics and uses these calculations to estimate more proximal joint kinetics. Consequently, inverse dynamics estimations rely on accurate estimation of the ankle joint as errors will be propagated and inflated with more proximal calculations. The previous studies on amputee running have not validated the methodology used for joint kinetic measurements with running-specific prostheses, which most likely will prove to be erroneous.[1-3] These limitations call for systematic research and development of validated models for running-specific prostheses. This will lead to improved prosthetic designs that will allow clinicians to provide evidence-based exercise prescriptions to amputees, enabling them to comfortably and efficiently run. The objective of the proposed study is to develop and validate a model with optimal set-up of reflective markers used in 3D gait analysis, producing minimal errors in inverse dynamics calculations. The long-term objective of this project is to understand the biomechanical and physiological consequences of amputation, to develop an optimal design of activity-independent lower-extremity prosthesis, and to help clinicians prescribing appropriate prosthesis and exercise regimes to people with a lower extremity amputation.

The current project was approved for funding over 18 months beginning 1 August, 2009 and to be completed by 28 February, 2011. The purpose of this document is to detail progress over the first 12 months of the study to satisfy the Annual Report requirement.

Body

The approved Statement of Work proposed the following timeline (Table 1):

Table 1. Timeline for approved project.

	Months 1-6	Months 7-12	Months 13-18
Specific Aim #1: Development and validation of a model with unique optimal marker placements for specific running prosthesis designs			
Formulate program for data analysis	X		
MTS testing of running specific prostheses (12 prostheses)	X		
Validation of model		X	
Analysis of MTS data to determine model		X	
Specific Aim #2: Determination of the resultant optimal marker placement for all tested running prosthetic designs			
Determine model with optimal marker placement for across designs			X

Specific Aim #1

MTS testing of running specific prostheses: *Completed*
The experimental setup was finalized and MTS testing was performed for the existing running-specific prostheses. A representative example of a prosthesis set up in the MTS machine is shown in Figure 2. Reflective markers were placed along the keel of the prosthesis in 1 cm increments and force transducers are present at the base and top of the experimental setup in order to measure forces and moments at the input (top) and “ground” level.

Formulating program for data analysis: *Completed*
Once raw experimental data were obtained from the MTS testing, we were able to being formulating the data analysis program in the Matlab programming language and validating the proposed model. Because the project is proposing a new model and method to analyze running-specific prostheses, each stage of the program development required validation to ensure proper measurements and calculations. Consequently, this is a lengthy progress involving a large amount of troubleshooting. The data analysis program has been completed. Please see preliminary data generated from this programming in the Reportable Outcomes section of this document.

Validation of model: *Near completion*
We are currently in the end stages of finalizing the validation of the programming and model so they may be used properly for the analysis of the MTS data to determine the final marker model. Due to the nature of developing a new model, it has taken slightly longer than originally anticipated to perform validation. We expect to complete model validation in 1 month.

Figure 2. Running-specific prosthesis (Ossur Flex-Run) setup in the MTS machine.

Analysis of MTS data to determine model: *Near completion*
Upon completing the full model validation, determining the final model for each specific prosthesis design will take approximately 1 additional month. Completing this task will complete the goals set for Specific Aim 1.

Specific Aim #2

Determine model with optimal marker placement for all prosthesis designs: *Expected On Time*
This task is proposed for Months 13-18 of the project and requires the completion of tasks in Specific Aim 1. Upon completing those tasks, we expect this task will be completed on schedule.

Unexpected Difficulties and Resolutions:

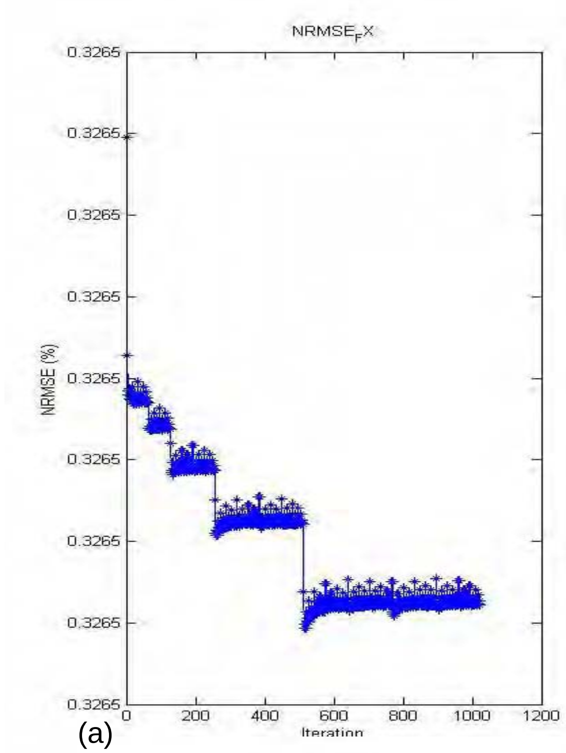
1. One of the prosthetic companies (Ossur) provided quotes to purchase running-specific prostheses during the grant preparation phase. These quotes were included in the grant proposal; however, during the attempted purchasing of the prostheses, the company claimed it would not sell devices to any person or entity other than a prosthetist.
    a. Resolution: We have been working with Ossur's representatives to allow the University of Maryland to set up a special account to allow prostheses to be purchased for research purposes. Upon purchasing the remaining prostheses, we will perform MTS testing. Prior experience with setup and testing will allow us to perform this testing within two weeks of obtaining the remaining prostheses.
2. Since this project is proposing the development and validation of a new model, the programming and validation element has taken longer than anticipated.
    a. Resolution: We have completed formulation of the program for data analysis, and we are finalizing the validation of the program and model. We anticipate full validation of these elements to occur in the next month.
3. The proper analysis of the MTS data to determine the marker model is dependent on the validation of the programming and model. Consequently, this portion of the project will follow the full validation of these elements.
    a. Resolution: Upon resolving Unexpected Difficulty 2 (we expect within the next month), the analysis of the MTS data will occur to determine the optimal marker model for each running-specific prosthesis design. We anticipate that this element will take approximately one month.

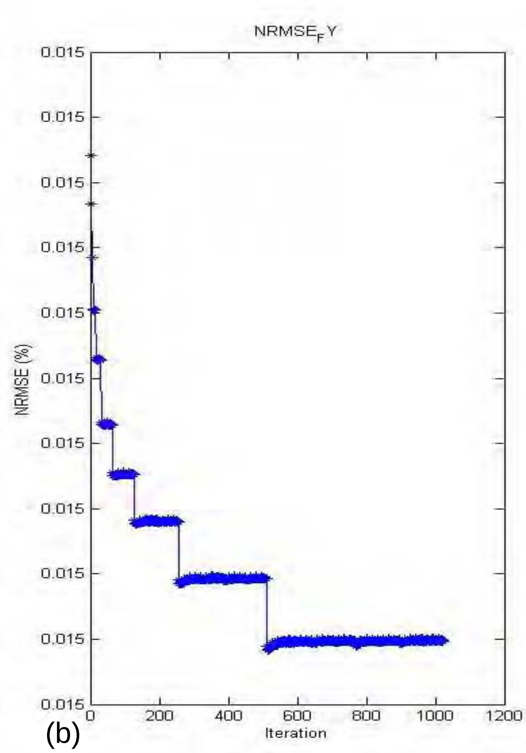
Key Research Accomplishments

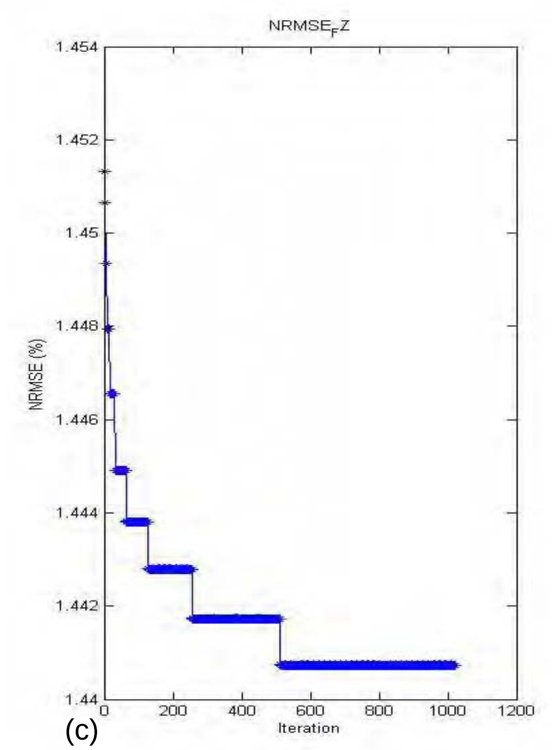
- Experimental setup and testing protocol is finalized.
  - The appropriate connections to secure the running-specific prostheses to the MTS machine have been fabricated and the method for the overall setup and testing of the prostheses has been completed (see Figure 2). Force transducers were connected to the MTS machine and a large bottom plate was installed on the lower transducer to provide a larger ground surface. Marker placements were measured and reflective markers were placed on the prostheses at 1 cm increments. The MTS machine controls the loading rate and force applied to the prostheses. Approximately 2300 N of force is applied at a cyclic loading rate of 1 Hz during testing.
- Formulation of the program for data analysis is completed.
  - Raw data from the MTS testing were used to construct the custom program needed for the data analysis. The Matlab programming language was used for this task. Inverse dynamics equations and the appropriate inputs for the equations needed to be formulated within the model. Additionally, adaptable code that allowed for inverse dynamics calculations for every possible combination of marker placement needed to be developed.
- Validation of the program and model has begun and is near completion.
  - Each subsection of the programming code has been tested and validated with examples and data from literature and academic texts. Since no projects or validated data exist that are similar to the current project, the code and model need to be validated with other data or known objects. We are in the process of using these data and objects to validate the fully completed program. Preliminary data that has not yet been validated have been generated for this annual report to show outcomes of the programming and model development progress. Please see the Reportable Outcomes section of this document for selected preliminary data.

Reportable Outcomes

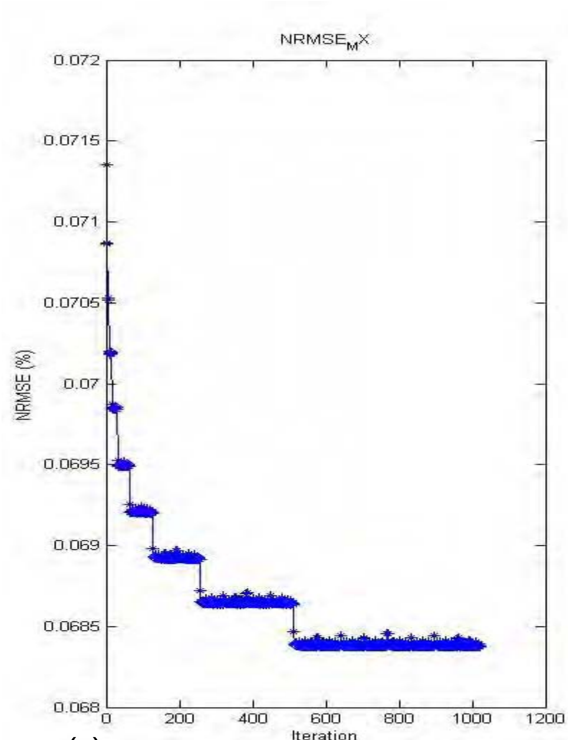
Preliminary data (not validated) are presented for normalized root mean square error (NRMSE), representing the difference (in percent) between the directly measured (via load cell) and estimated (via inverse dynamics) proximal forces and moments calculated for 1024 iterations of possible marker combinations. Each point on each graph represents the error for a different possible combination of markers placed on a prosthesis. NRMSE for forces are shown in Figure 3 while NRMSE for moments are shown in Figure 4.



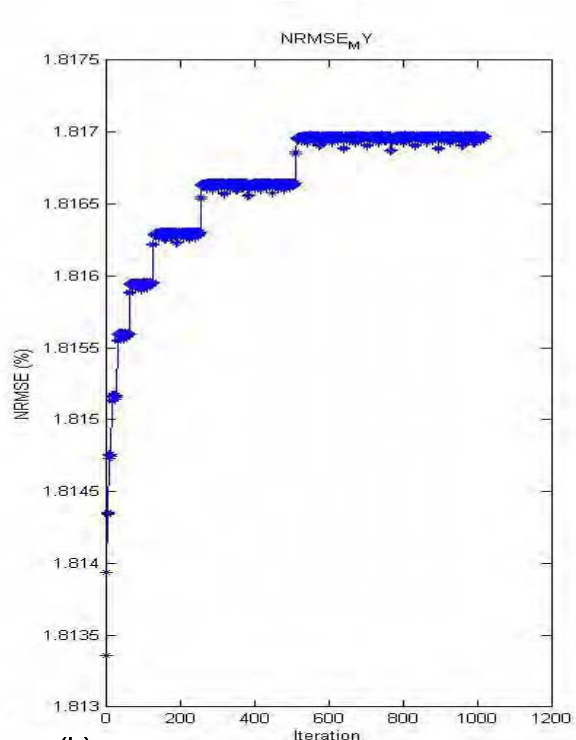




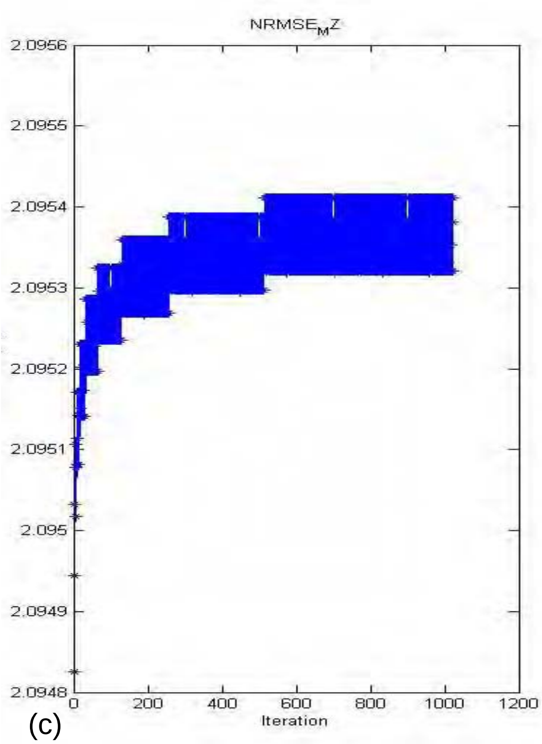
Figures 3a-c. Normalized root mean square error (NRMSE, %) between the estimated (via inverse dynamics) and directly measured (via load cell) force in the (a) X, (b) Y, and (c) Z directions for the Flex-Run prosthesis.



(a)



(b)



(c)

Figures 4a-c. Normalized root mean square error (NRMSE, %) between the estimated (via inverse dynamics) and directly measured (via load cell) moment in the (a) X, (b) Y, and (c) Z directions for the Flex-Run prosthesis.

Conclusion

Overall the progress of the research is on track. Some unexpected difficulties have slightly delayed portions of our proposed research by approximately one month; however, these issues are being resolved and are not expected to affect the on time and successful completion of the project.

The preliminary data shown in the Reportable Outcomes section will allow us to identify the iterations (combinations of marker placements) that yield acceptable error between the estimated (via inverse dynamics calculations) and directly measured (via load cell) force and moment values upon full validation of the program and model. These data will yield recommendations for marker placement on running-specific prostheses that will guide future research.

The preliminary results presented in the Reportable Outcomes section also suggest that the marker combinations tested result in errors of less than 2.1% for force and moment calculations. If these data remain consistent after fully validating the programming code and model and after testing all combinations of marker placements on the prostheses, then only a limited number of markers will be needed on a running-specific prosthesis for accurate joint kinetic analyses. This will allow a larger number of research laboratories to perform running analyses since fewer motion capture cameras would be needed to perform the analysis. This will also dramatically reduce the setup time (fewer markers = less time spent during setup) and the impact on the individual being tested.

We anticipate the successful completion of the research protocol and data analysis on time barring any other unexpected difficulties.

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