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Computational Biomechanics in Cross-country Skiing

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Cover:

Visualization of simulation model a few time steps into the poling phase. Double-poling skier building up force to push forward.

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Preface

The majority of the work in this thesis was carried out at the Department of Engineering, Physics and Mathematics, Mid Sweden University in Östersund, Sweden. All experimental work was carried out at the Swedish Winter Sports Research Centre at Mid Sweden University in Östersund, Sweden.

First of all I would like to thank Björn Esping for inspiring and hiring me in the first place.

Many thanks to Anders Klarbring at the Division of Mechanics, Linköping University, for taking me on as an external PhD student.

I would also like to thank my former colleagues at the Department of Engineering, Physics and Mathematics, Mid Sweden University in Östersund. A special thanks to long time friend Lasse Rännar.

For their hospitality, and for sharing their ideas, software and time on workshops and visits, I am in debt to the AnyBody group at Aalborg University in Denmark.

HC, thanks for the fruitful discussions, and let them carry on.

Marie Lund, I would be out of a job with no degree if it wasn't for you.

Finally, I would like to thank my family for their patience and support.

St. Christoph am Arlberg, December 19, 2007

Joakim Holmberg

Abstract

Traditionally, research on cross-country skiing biomechanics is based mainly on experimental testing alone. Trying a different approach, this thesis explores the possibilities of using computational musculoskeletal biomechanics for cross-country skiing. As far as the author knows, this has not been done before.

Cross-country skiing is both fast and powerful, and the whole body is used to generate movement. Consequently, the computational method used needs to be able to handle a full-body model with lots of muscles. This thesis presents several simulation models created in the AnyBody Modeling System, which is based on inverse dynamics and static optimization. This method allows for measurement-driven full-body models with hundreds of muscles and rigid body segments of all major body parts.

A major result shown in the thesis is that with a good simulation model it is possible to predict muscle activation. Even though there is no claim of full validity of the simulation models, this result opens up a wide range of possibilities for computational musculoskeletal biomechanics in cross-country skiing. Two examples of new possibilities are shown in the thesis, finding antagonistic muscle pairs and muscle load distribution differences in different skiing styles. Being able to perform optimization studies and asking and answering "what if"-questions really gives computational methods an edge compared to traditional testing.

To conclude, a combination of computational and experimental methods seems to be the next logical step to increase the understanding of the biomechanics of crosscountry skiing.



Sammanfattning

Traditionellt har biomekaniska forskningsstudier av längdskidåkning baserats helt och hållet på experimentella metoder. För att prova ett annat angreppssätt undersöks i denna avhandling vilka möjligheter som beräkningsbaserad biomekanik kan ge för längdskidåkning. Så vida författaren vet, har detta inte gjorts tidigare.

Längdskidåkning innehåller snabba och kraftfulla helkroppsrörelser och därför behövs en beräkningsmetod som kan hantera helkroppsmodeller med många muskler. Avhandlingen presenterar flera simuleringsmodeller skapade i AnyBody Modeling System, som baseras på inversdynamik och statisk optimering. Denna metod tillåter helkroppsmodeller med hundratals muskler och stelkroppssegment av de flesta kroppsdelarna.

Ett resultat som avhandlingen visar är att med en bra simuleringsmodell är det möjligt att förutsäga muskelaktiviteten för en viss rörelse och belastning på kroppen. Även om ingen validering av simuleringsmodellen ges, så visar ändå resultatet att beräkningsbaserad biomekanik ger många nya möjligheter till forskningsstudier av längdskidåkning. Två exempel visas, hur muskelantagonister kan hittas samt hur lastfördelningen mellan musklerna förändras då skidåkaren förändrar stilen. Att kunna genomföra optimeringsstudier samt fråga och svara på "vad händer om"-frågor ger beräkningsbaserad biomekanik en fördel i jämförelse med traditionell testning.

Slutsatsen är att en kombination av beräkningsbaserade och experimentella metoder borde vara nästa steg för att addera insikt om längdskidåkningens biomekanik.



List of papers

This thesis is based on the following five papers:

- I. Holmberg, J. and Rännar, L-E. Versatile Optimization. Nordic MATLAB Conference Proceedings, 207-212, Oslo, Norway, October 17-18 2001.
- II. Holmberg, J. and Wagenius, P. A biomechanical model of a double-poling skier. In International Society of Biomechanics XIXth Congress on The human body in motion, CD Rom Abstracts and Proceedings, Milburn, P. (Ed.), University of Otago, Dunedin, New Zealand, 6-11 July 2003.
- III. Lund, A. M. and Holmberg, L. J. Which are the antagonists to the pectoralis major muscle in 4th gear free-style technique, cross-country skiing? In Science and Nordic Skiing, Linnamo, V., Komi, P.V. and Müller, E. (Eds.), 2007, Meyer and Meyer Sport, Oxford, UK, pp. 112-118.
- IV. Holmberg, L. J. and Lund, A. M. Using double-poling simulations to study the load distribution between teres major and latissimus dorsi. In Science and Nordic Skiing, Linnamo, V., Komi, P.V. and Müller, E. (Eds.), 2007, Meyer and Meyer Sport, Oxford, UK, pp. 81-89.
- V. Holmberg, L. J. and Lund, A. M. A musculoskeletal full-body simulation of cross-country skiing. Submitted for publication.

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Part 1 – Introduction

Background and aim of thesis

The aim of this thesis is to explore the possibilities for computational musculoskeletal biomechanics in cross-country skiing. Two questions arise: 1) Why study cross-country skiing? 2) Why should computational musculoskeletal biomechanics be used?

To answer the first question and answer it honestly, one has to consider the location where most of the work in this thesis was carried out. In Östersund, Sweden, there is winter with skiable snow several months each year. Naturally, there is a great deal of local interest in cross-country skiing, not only among the general public and the sports community but also within the scientific community, i.e. the local university. Apart from the location issue, cross-country skiing is interesting because it is a complex full-body movement and the skiers are very well trained athletes. Also, the skier interacts with both equipment (boots, skis and poles) and the physical surroundings (snow, wind and track inclination). All this makes scientific studies both easier and more challenging. Easier, because a physically well trained athlete is able to adapt to technique and equipment changes; more challenging because it is probably hard to improve physical fitness and some of the interactions can be hard to model or measure.

The short answer to the second question is that computational musculoskeletal biomechanics has not been used to study cross-country skiing before. Actually, the biomechanics of cross-country skiing has not been studied extensively and there seems to be no deeper understanding of why some skiers are faster than others. So far, biomechanical studies have been based on traditional testing alone. Most studies treat only kinematics. A few studies also include some external kinetics by measuring pole forces. Even fewer include internal kinetics by measuring muscular activity using electromyography. There is a need for more experimental electromyography studies that also includes kinematics and external kinetics [1]. However, electromyography has its limitations; one is that it is hard to measure muscles that are not superficial. With computational musculoskeletal biomechanics it is not harder to achieve results for deep laying muscles, which is one reason to use computer simulations. Other reasons are the possibility to ask and answer "what if"-questions and to perform optimization studies. Admittedly, computational methods also have limitations that will be discussed further on. Nevertheless, a combination of computational and experimental methods seems to be the next logical step in crosscountry skiing biomechanical research.

There are several techniques in cross-country skiing, and in order to keep the simulations simple, the double-poling technique is chosen for the studies in most of the papers included in this thesis. Double-poling takes place mainly in the so called sagittal plane, i.e. it is essentially two-dimensional. This feature of double-poling

makes it easier to capture the motion as well as creating the simulation model used in the computations.

To sum up, there is a lack of studies in cross-country skiing using computational methods. The research question, or simply put the aim, of this thesis is therefore to explore the possibilities for computational musculoskeletal biomechanics in cross-country skiing. What can be done and to what extent?

Solution strategy and problem definition

For a computer simulation of double-poling biomechanics there are several computational methods to choose from. At the time when this work was started, inverse dynamics and static optimization was considered as the only possible choice due to the complexity of the motion, computation time and a wish to include a large number of muscles. In addition, the AnyBody Modeling System (software using inverse dynamics and static optimization for musculoskeletal biomechanics developed at Aalborg University) was just released, thus making it possible to focus on the development of a simulation model for cross-country skiing, instead of the fundamental mechanics of the method [2]. Today, the choice would perhaps not be as obvious due to the rapid development and enhancement of different methods in recent years [3].

Inverse dynamics can be viewed as when a prescribed motion drives the body model, and the internal forces needed to generate this motion are sought. In musculoskeletal inverse dynamics the muscles are recruited to work so that the body performs the prescribed motion. Unfortunately, for most movements the human body is a redundant system, i.e. there are more muscles than necessary to perform the movements. To find the force sharing between the muscles, a strategy to do so is needed. The muscle load distribution is assumed to be optimal in some sense and is formulated as a mathematical optimization problem. The AnyBody Modeling System uses a min/max formulation that yields a minimum fatigue criterion in the sense that it enforces minimal activity of the maximally activated muscles [4]. The reason for calling it static optimization is that the load distribution is solved for each time step in the simulation. The problem with this strategy is that, currently, it is not possible to include activation dynamics for the muscles. Cross-country skiing involves fullbody movements with high accelerations, causing high forces. This is a potential problem when using the method, inverse dynamics and static optimization, for this application, cross-country skiing [5].

For inverse dynamics, motion and external forces are the boundary conditions. Most of the studies in this thesis have measured boundary conditions from a so called double-poling ergometer. On the ergometer, the poles tips are fixed to the rest of the mechanism with spherical joints. Load cells are placed between the pole and the joint, enabling pole forces to be measured in the axial direction. On the other hand the skier has to do considerable work to move the poles forward which is not the

case in real double-poling. This experimental set-up is not ideal, but makes it possible to achieve results with limited resources.

Summary of papers

Paper I - Versatile Optimization

This paper describes an optimization environment implemented in MATLAB called VerOpt, which contains several optimization routines and the possibility to execute them in parallel. The paper gives a simple example of a standard optimization formulation, and a schematic flow on how to use external solvers and how to execute the optimization routine in parallel. It also compares the different optimization routines for a few test problems, executed both sequentially and in parallel. Results showed that some optimization routines were more efficient than others, depending on problem type. Also, results showed that there is time to be gained by using parallel optimization. Until recently, AnyBody had no facility for external optimization. There is one now, but there is no possibility to choose from different optimization routines or to execute in parallel. In Paper V, discussed later on, the solution time for one run is about 20 minutes. Using optimization, to find the optimal pole length for example, might take numerous runs. Being able to use parallel optimization saves time.

Paper II – A biomechanical model of a double-poling skier

This paper introduces cross-country skiing and biomechanical analysis of double-poling. Some of the research problems and potentials are discussed. To gather boundary conditions a double-poling ergometer was used. Unfortunately, there were no load cells installed at the time and the ergometer power readings are of little use when studying one individual poling cycle. Therefore, a pole force curve from literature was used. The body model consisted of the right side of the upper body and had a Hill-type muscle model. This body model was partially developed by students and the authors. Even though the body model could not fully cope with the external forces, simulation results showed similarities with literature. The conclusion was that the method, computational musculoskeletal biomechanics, had a potential for cross-country skiing. Lessons learned for future work were that all boundary conditions should originate from the same measurement and that the best possible body model should be used, preferably with a simpler muscle model.

Paper III – Which are the antagonists to the pectoralis major muscle in 4th gear, freestyle technique, cross-country skiing?

In 4th gear, freestyle technique, the range of motion for the upper arm is very large. Some skiers have a muscular imbalance around the shoulder, i.e. the chest muscle pectoralis major is strong compared to its antagonists, causing bad posture. This imbalance hinders the back swing of the arm, probably making the movement less effective. Training the antagonists to pectoralis major should correct the muscular

imbalance and improve the arm swing. The idea was to find the antagonists using a biomechanical simulation. Boundary conditions originated from a measurement in three dimensions with a motion capture system, but with gravity as the only external force (no pole force). The body model was a three-dimensional upper body model originating from the AnyBody Model Repository, a public domain collection of musculoskeletal models. All muscles except pectoralis major had a constant force muscle model. Pectoralis major had a Hill-type muscle model and by experimenting with the tendon length, increasing passive resistance, the antagonists were found. Simulation results showed that rhomboideus, infraspinatus, trapezius (scapular parts) and latissimus dorsi (extending parts) are the antagonist muscles to pectoralis major in 4th gear, freestyle technique, cross-country skiing. It is worth pointing out that the research question in this study came from the skiing community.

Paper IV – Using double-poling simulations to study the load distribution between teres major and latissimus dorsi

Recent electromyography studies found in literature show that, depending on double-poling style, there is a difference in the load distribution between the muscles teres major and latissimus dorsi. If a biomechanical simulation would give the same result, it would be an indication that the method is reasonable. Results from literature also show that leg work is important for the overall result in double-poling. Therefore, a three-dimensional full-body model, originating from the AnyBody Model Repository, was used. The body model had a constant force muscle model. Boundary conditions were extracted from an experiment with a skier on a doublepoling ergometer equipped with load cells at the pole tips. The body model could not handle the external forces to a full extent. Hence, pole forces had to be scaled down. By changing the arm motion slightly, it was possible to simulate the different doublepoling styles. Simulation results were consistent with those found in literature. With greater arm abduction and smaller elbow angle at pole plant, teres major carried more of the load, in the sense that muscle activation increased more for teres major than it did for latissimus dorsi. This research question also came from the skiing community.

Paper V – A musculoskeletal full-body simulation of cross-country skiing

In this paper a measurement-driven musculoskeletal three-dimensional full-body biomechanical simulation of cross-country skiing is presented. For the first time, the simulation model is reasonably stable and the body model can handle realistic loads. The inside (basic equations, body model and boundary conditions) of the simulation model is presented and simulation results are compared to literature. Again, the body model originated from the AnyBody Model Repository and had a constant force muscle model. Boundary conditions originated from the same experiment as in paper IV, but were used in a slightly different manner resulting in a more stable simulation model. The comparison with literature showed that when the motion and

external forces were similar, the muscle activities match. Consequently, it was concluded that the chosen method yields realistic internal body loads for this application, which is a skilled but fast full-body movement.

Conclusions

As stated, the aim of this thesis is to explore the possibilities in using computational musculoskeletal biomechanics for cross-country skiing. Especially in paper III and IV, two different, but both very interesting possibilities are shown. Paper V shows a fully functional simulation model that opens up a wide range of possibilities. What really gives computational biomechanics an edge is the possibility to ask and answer "what if"-questions and also to perform optimization studies. For example, what if the elbow angle is changed at pole plant, what happens with the load distribution in the body?

There are still some problems with the validity of the method. In this thesis, and the papers it largely consists of, no proof of validation of the method or the simulation model is given. Even so, the results can still be very useful as shown in the papers, and the conclusion is that computational biomechanics is a valuable addition to traditional, experimental-only, studies of cross-country skiing.

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