A BIOMECHANICAL MODEL OF A DOUBLE-POLING SKIER

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INTRODUCTION

Skis have been used as means for transportation in Scandinavia for thousands of years, that is, if rock carvings and other remnants found (Berg, 1950) are to be trusted. Probably the most important ski race and also one of the first known to the authors took place in 1520. The young rebel Gustav Vasa had been imprisoned by the Danes but managed to escape, and while he was chased by the Danes Vasa traveled north through Sweden looking for support to throw the Danes out of Sweden. When he came to the Swedish province of Dalarna he tried to convince the people to support him in a war against Denmark, but before he received a response the Danish chasers were getting too close. Vasa took his skis and headed for Norway. Nevertheless, the people in Dalarna decided to help him and two men raced after him. Vasa had traveled 89 kilometers and was very close to the Norwegian border before he was caught up. Since 1922 there is an annual race called Vasaloppet with about 15,000 participants covering the same ground and distance. And yes, Vasa and the people in Dalarna drove the Danes out of Sweden. Later on, Vasa was appointed King of Sweden.

Until the arrival of “skating” (quotation marks are used since “skating” defines a base technique used in several very similar but different skiing techniques) in the mid eighties, there had not been much development in cross-country skiing since 1922. The diagonal stride technique was dominating and occasionally complemented with the kick double-pole technique and the double-pole technique. When “skating” arrived on the cross-country scene it changed the sport dramatically since it was possible to ski much faster with the new technique. And since all competitors used “skating” there was a concern that classical skiing would become obsolete. Thus, it was ruled that half of all World Cup cross-country ski races would be “classical” and the other half would be “free-style” in which “skating” is dominating. The name “skating” originates from the resemblance to speed skating regarding the leg movement pattern.

During the last decade there has been a rapid development in cross-country skiing, especially in “skating”. This development comprises new materials for skis and poles, longer poles and different “skating” techniques. Moreover, changes also take place in the classic discipline of cross-country skiing. For example, improved skis along with better prepared tracks are mentioned as one reason for the trend among elite skiers to use the double-poling technique more frequently (Holmberg, 1996). Even though primary developed for “skating”, the longer poles used is brought up as another reason for the more frequent use of double-poling (Hoffman and Clifford, 1992). The longer poles seem to have improved the relative economy of this technique by enhancing the use of gravitation and the upper body musculature. Hoffman and Clifford propose that it is possible that the mechanics of double-poling allow for better storage and utilization of elastic energy, particularly when longer poles are used.

Even though there is a higher demand for upper body strength when using the double-poling technique compared to the traditional diagonal stride technique, there is a decrease in back injuries according to a retrospective epidemiological study of lower back pain among elite cross-country skiers (Eriksson et al, 1996). As seen in Table 1, diagonal stride is the most common pain-inducing technique.

Table 1: Localization of back pain and back pain correlated to skiing techniques (adapted from Eriksson et al, 1996)

	Males	**Females**
Lower back pain	97 %	90 %
Back pain when double-poling	33 %	70 %
Back pain when diagonal striding	91 %	75 %
Back pain when “skating”	21 %	30 %

Since demands on upper body strength are higher for double-poling, why is diagonal stride the most common pain-inducing technique? In the study by Eriksson et al it is speculated that compared to double-poling and “skating”, the diagonal stride induces more static stress in the lower back (erector spinae), which if true, could be a reason for the higher percentage of back pain. The study also shows that there are differences between males and females. Among females back pain is very common even when double-poling. Why is that? Well, the flexion of the upper body is much greater when double-poling than when “skating” or using the diagonal stride. Do elite female cross-country ski competitors have a weak trunk comparatively to male skiers? If that is the case, it could be one reason for the high percentage of back pain among females when using the double-poling technique.

There has also been a study on the movement pattern of double-poling to answer the question concerning which muscles are active in the movement and in what order (Nilsson and Holmberg, 2000). Another question related to the double-poling technique is what muscles are most important for elite performance? And, as a consequence, what would be the result if movement patterns and muscle strength were different? Could the performance excel even more?

Apart from the material mentioned above, previous research on cross-country skiing found by the authors mostly considers physiological aspects like oxygen uptake and anaerobic thresholds. Recent findings include how to measure these factors (Wisløff and Helgerud, 1998) and how to train in order to enhance them (Hoff et al, 1999). There have also been studies of poling forces where different grades (inclines), skiing techniques and speeds have been compared (Millet et al, 1998a; Millet et al, 1998b). A study of the kinematics of cross-country skiing showed that cycle length is very important for success in racing for all techniques except double-poling (Bilodeau et al, 1996).

To conclude, except for a Bachelor thesis (Hartung and Sjöström, 2000) carried out at Mid Sweden University, to the best of the authors' knowledge, there have not been any previous biomechanical studies on cross-country skiing using numerical techniques.

Double-poling is appealing to the authors since it primary is a two-dimensional (2D) movement that takes place in the sagittial plane. A movement in 2D is much easier to model with mechanics and numerical techniques compared to a movement in three dimensions. Also very appealing is since that double-poling is considered to be a technique where the upper body does most of the work, it should not be pointless to start with a model that only comprises the upper body and the poles. With the questions raised above in mind, this paper presents a biomechanical model of a double-poling skier, designed in a way that allows such and similar questions to be simulated and hopefully answered.

METHODS

The model is created with the use of AnyBody (www.anybodytech.com), a general body-modeling and optimization software. AnyBody applies a technique called inverse-inverse dynamics to simulate the human movement (Rasmussen et al, 2000). Inverse dynamics means that a given movement powers the body, and that the muscle forces needed to produce that movement are computed by the software. However, there can be many ways to make a certain movement, and therefore an optimization, using a minimum fatigue criterion, is carried out in order to attain the best muscle load distribution. Thus, an inverse-inverse dynamics algorithm is created.

The elements of an AnyBody model are:

- Segments; bones and other rigid bodies like skiing poles which are given mass and mass inertia properties that is used in the kinematics.
- Joints; these connects the segment to each other.
- Drivers; models in AnyBody move by means of drivers, which are kinematical constraints specifying a position of a point or a joint at a given time.
- Muscles; these provide the work needed to produce the movement that the drivers specify, AnyBody uses a modified Hill-type muscle model (Zajac, 1989).

Since AnyBody needs movement as input a physical experiment is performed. An elite female skier is video-taped while using a double-poling ergometer. This experiment provides measurements of the movement in the sagittial plane and also the poling power. The double-poling ergometer (Figure 1) used is specially designed to simulate the double-poling movement. This apparatus is a modified rowing ergometer (Concept II C, Concept Inc., Morrisville, VT, US). The skier stands on a podium above the slide rail. The ergometer has poles attached to a metal bar that is mounted on a slide wagon. The wagon is connected to a fixed pulley system by means of a cord. The pulley is connected to a chain which drives the air friction braked flywheel by means of a cog-wheel.

Figure 1: Skier on a double-poling ergometer.

A series of 30-second measurements are conducted during the experiment. These are recorded using a simple analogue video camera mounted on the wall in the laboratory. After a manual inspection of the video, one measurement with consistent double-poling cycles is chosen as the basis for movement extraction and poling power comparison. The analogue video sequence of the chosen measurement is digitized and saved as a digital video file with a frame rate of 25 frames per second. Studying individual video frames the cycle rate is determined to about 1.4 seconds. Also, individual video frames from a full cycle are saved as images. Using these images, selected joint angles and the position of the pole tip are measured. The computer software used for the digitizing and movement extraction process are Adobe Premiere (www.adobe.com), VirtualDub (www.virtualdub.org) and Rhinoceros (www.rhino3d.com).

The AnyBody model in this paper is created based on an artificial skeleton with roughly the same anatomical measures as the skier. Of course, this means that many approximations have been done. Also, since the movement is primary in 2D and symmetrical, only the right side of the upper body and the right pole are included in the model. Major simplifications are a rigid spine, no shoulder movement in the sagittial plane and the lack of a proper hand. A visualization of the model can be seen in Figure 2.

Figure 2: AnyBody model of a double-poling skier.

The model consists of the following segments: hip, trunk, upper arm, lower arm, hand and a pole. All segments are connected to each other via joints. These joints are modeled as hinges.

All anthropometric muscle data in the model comes from the thesis by Hartung and Sjöström.

Muscles included in the model are:

- Spine & Thorax
    - Latissimus Dorsi
    - Pectoralis Major
- Shoulder girdle
    - Deltoideus
    - Teres Major
    - Teres Minor
    - Coracobrachialis
    - Infraspinatus
    - Subscapularis
    - Supraspinatus
    - Biceps Brachii Caput Longum
    - Triceps Brachii Caput Longum
- Arm skeleton
    - Brachialis
    - Triceps Brachii Caput Laterale
    - Triceps Brachii Caput Mediale
    - Pronator Teres Caput Humerale
    - Pronator Teres Caput Ulnare
    - Brachioradialis
    - Extensor Carpi Radialis Longus
    - Extensor Carpi Radialis Brevis
    - Extensor Digitorum
    - Extensor Digiti Minima
    - Extensor Carpi Ulnaris
    - Flexsor Carpi Radialis
    - Palmaris Longus
    - Flexsor Caput Ulnaris
    - Pronator Quadratus
    - Flexsor Digitorum Superficialis
    - Flexsor Digitorum Profundus
    - Flexsor Pollicis Longus
    - Abductor Pollicis
    - Extensor Pollicis Brevis
    - Extensor Pollicis Longus
    - Extensor Indicis
- Stomach muscles
    - Rectus Abdominis
    - Obliquus Externus Abdominis
    - Obliquss Internus Abdominis
- Back muscles
    - Multifidi
    - Erector Spinae

Also in the model are two artificial finger muscles (not shown in Figure 2).

The model is driven by the extracted data from the measurement. Those drivers are: translation of the hip in the sagittial plane, hip rotation, shoulder rotation (upper arm rotates with respect to the trunk), wrist rotation and position of the pole tip.

To simulate the force in the pole when double-poling, a force is applied at the tip of the pole. It is directed "upwards" axially through the pole making the muscles work to counteract it. The pole force used is approximated from Millet et al (1998b), see Figure 3.

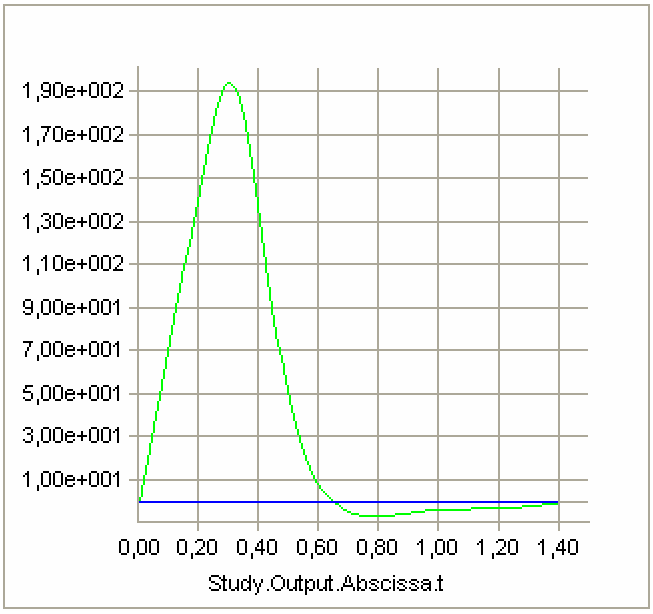

Figure 3: Pole force used in the AnyBody model.

RESULTS AND DISCUSSION

In this first study that is presented here, simulation results (see Figure 4-6) are compared with the experiment concerning muscle activation sequences (Nilsson and Holmberg, 2000). That experiment shows that double-poling can be described as a three stage rocket. First, the hip and stomach muscles are activated and then, the shoulder girdle muscles and at last, the muscles that span the elbow. Measured muscles with electromyography (EMG) in the experiment were rectus femoris, rectus abdominis, latissimus dorsi and triceps bracii.

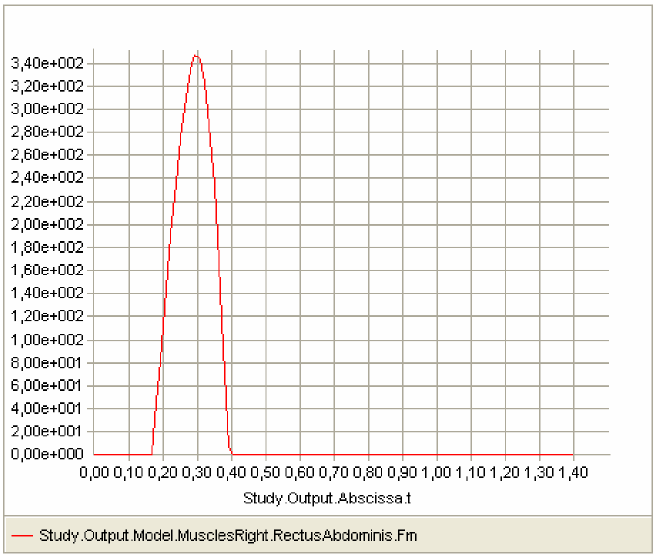

Figure 4: Force generated by rectus abdominis.

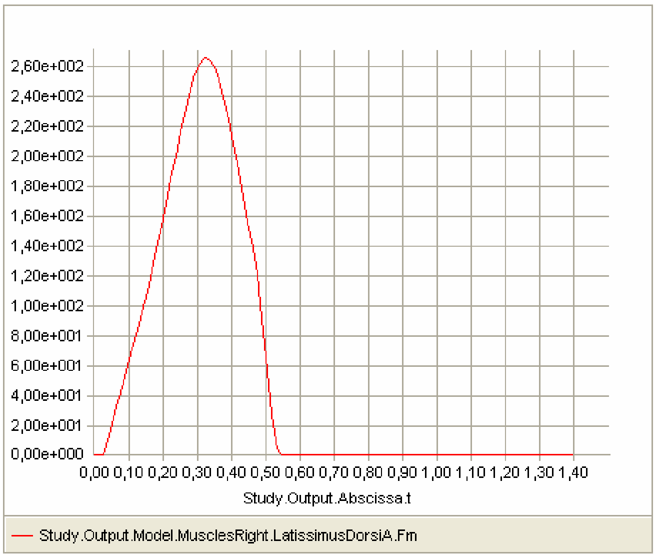

Figure 5: Force generated by latissimus dorsi.

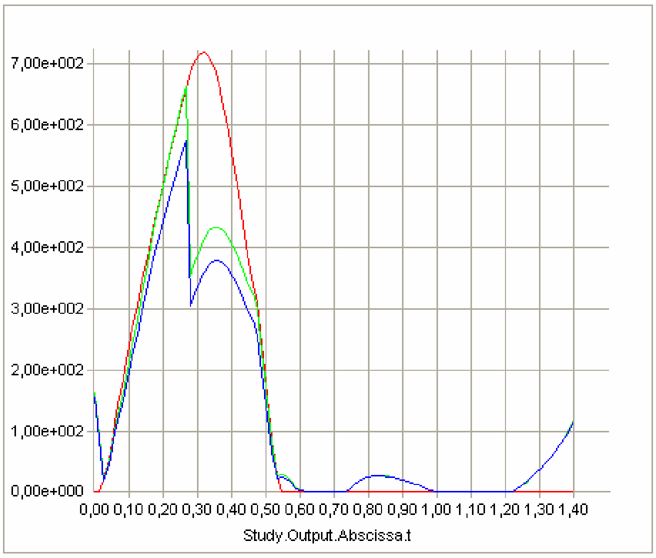

Figure 6: Force generated by the three triceps in the model.

When inspecting simulation results (Figure 4-6) it can be seen that the activation sequence agree well for the muscles rectus abdominis and latissimus dorsi. The simulation result for the three triceps agrees fairly well. In Figure 6, the curve with one peak only is for triceps brachii caput longum. Since that muscle spans not only over the elbow, but also over the shoulder, it is not surprising that it peaks at the same time as latissimus dorsi during the poling cycle. The other two triceps, caput laterale and caput mediale, spans only over the elbow. Ignoring the discrepancy in the beginning of the cycle, they also fits the pattern very well. Also, the peak found in the middle of the return phase agrees very well with the findings of Nilsson and Holmberg. A specific reason for the discrepancy found in this comparison is not known, but one guess is a too faulty approximation of the origin point for the two triceps that span only the elbow.

Simulation results do not agree with measured poling power. This suggests that much better anthropometric muscle data is needed and also a pole force that corresponds to actual poling on the ergometer.

There are numerous other reasons for the discrepancies found than those mentioned above. For example, the phase when extracting the data from the still images is critical since it is a possible source of measurement error. One reason is the wide angle lens on the camera distorting the image. Another reason is the extensive level of subjective interpretation when manually measuring the joint angles. Even though the excellent tools in the software Rhinoceros are used, it is a definite source of error in this paper.

One big and very important step towards creating a good model is to attain a more precise movement pattern. What is needed is a method that is not as error prone as the one used in this paper. Also, very important is a good measurement of the poling forces. Ideally would be to measure both movement and poling forces at the same time.

What the model also needs is the addition of a right leg, a right foot and a more detailed hip (pelvis). For example, ilipsoas is a very important muscle for double-poling (Holmberg, 1996). Examples on muscles that should be included in a “2D full-body” model are:

- Soleus
- Gastrocnemius
- Tibialis Anterior
- Vastus Lateralis
- Vastus Medialis
- Vastus Intermedius
- Rectus Femoris
- Semitendinosus
- Semimembranosus
- Biceps Femoris Caput Longum
- Biceps Femoris Caput Breve
- Iliopsoas
- Gluteus Maximus

With a “2D full-body” (including a left side), there could also be studies of the diagonal stride and the kick double-pole. However, it might be a lot harder to find accurate boundary conditions for those two techniques. But if that problem can be solved, several possibilities of numerical-based comparisons of the classical cross-country skiing techniques would emerge.

However, there is much to be done before a biomechanical model that is a good representation of reality can be created. Still, the method presented here shows good potential and could very well be used for initial studies of the questions raised in the introduction.

According to Hoffman (1992), no publications have compared the economy of double-poling with a wide range of pole lengths. The authors have not found such a publication either, even though it is more than ten years since Hoffman’s statement. The model presented here could very well be used for an initial study in this area. And when the method used here becomes more reliable, it would be possible to adapt a model for a specific individual and then optimize the pole length for double-poling.

What really gives this method an edge, compared to traditional testing, is that with a biomechanical model based on numerical techniques, there is the possibility to utilize mathematical optimization techniques for achieving better results regardless whether that is to win races or for the prevention of injuries.

SUMMARY

Up till now, very little has been done in the field of cross-country skiing biomechanics using numerical techniques.

This paper presents a biomechanical model of a double-poling skier that is created with the use of AnyBody, a general body-modeling and optimization software. As an aid to validate the model, a physical experiment is performed. An elite female skier is video-taped while using a double-poling ergometer. This experiment provides measurements of movement and poling power.

Simulation results agree well with an experiment concerning muscle activation sequences (Nilsson and Holmberg, 2000). However, when simulation results and measured poling power are compared, agreement is not good. This means that further work on the biomechanical model is needed before it can be validated as a good representation of reality. Still, the method shows potential, and the present model could be used for initial studies of the double-poling technique. When the model is validated, it could provide a very useful tool in the quest for gold medals and perhaps, more importantly, for the prevention of injuries.

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