TESTING OF CROSS-COUNTRY SKI SHOES USING AN INDUSTRIAL ROBOT

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INTRODUCTION

Shoes are an important part of the sports equipment. They are constantly developed and improved. This is especially evident for winter sports, alpine skiing, cross-country skiing, skating, etc. Usually, the design of ski boots is based on a trial and error method, where each prototype is tested on the outdoor terrain. This approach is very time consuming and expensive. It is affected by the personal judgement of the tester. Recently, sport scientists, athletes and shoe manufacturers have raised the possibility that a cross-country ski boot can enhance the energy efficiency of the ski runner. They suspect that very small changes in energy return characteristics can help to improve the sports results. However, it is not yet clear how to measure this benefit (Shorten, 1993). In the past a numerous studies were done dealing with the testing of running shoes (Nigg 1986, Barry and Milburn 1999), but very few were dealing with the alpine skiing boots and cross-country skiing boots. In the paper, we propose an approach to the sports equipment testing based on the simulation of the sport activity with an industrial robot. It consists of two major phases: a measurement phase and a simulation phase. In the measurement phase we capture the forces and trajectories that occur during the sport activity. The sport activity is recorded also with a video camera, which enables identification of the movements during the simulation phase. In the simulation phase, we use an industrial robot that repeats the captured motion. With additional measurement equipment, various forces, tensions, vibrations, etc. can be measured at any part of the sport shoe. The main benefit of this approach is that various shoes can be measured and compared under the same conditions. Additionally, laboratory environment makes possible measurements that are very difficult or impossible to perform on the terrain. The method was successfully applied for the testing of cross-country and alpine skis (Nemec, 98) Here, application to the cross-country ski boots will be described. The efficiency of the proposed method is illustrated by comparing two types of the ski boots. Test trajectory was obtained from an elite cross-country skier.

METHODS

measuring of kinematic and dynamic parameters of cross country skiing

Measuring of the kinematic and dynamic parameters of the cross-country skiing requires measuring of the movement of the skier's shank relative to the skis and the resulting ground reaction forces. Movement of the skier's shank was obtained using the ELITE optical measuring system for indoor measurements and the ARIEL optical measurement system for outdoor measurements. The ELITE system consists of four video cameras that can detect infrared light reflected from markers and a computer program that computes 100 positions of the markers per second relative to a fixed coordinate frame. The marker placement for measuring movements during cross-country skiing is presented in figure 1.

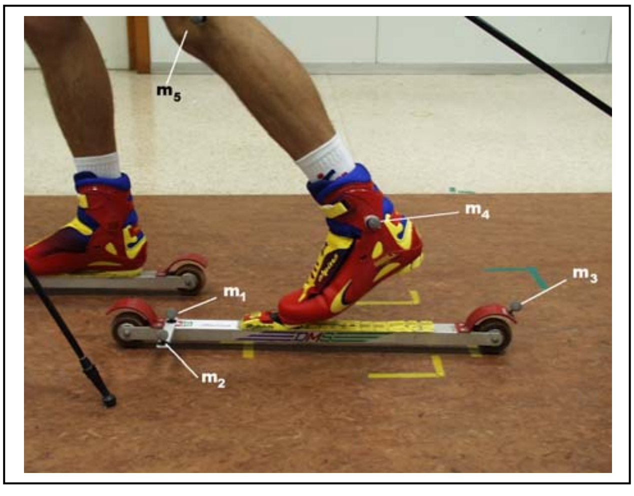

Figure 1 Marker placement

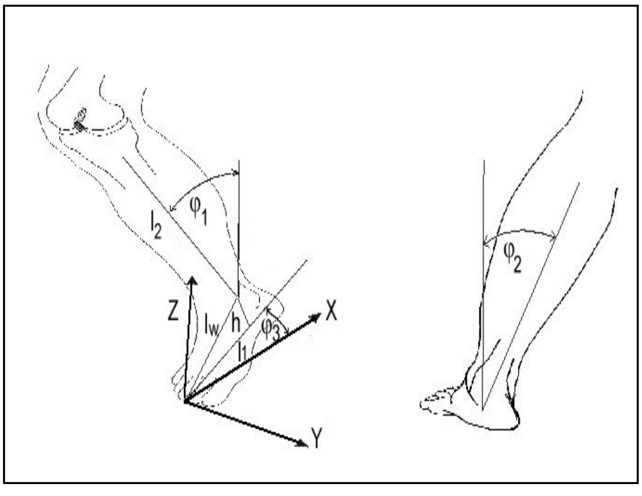

Figure 2 Shank angles

When the cross-country skiing is simulated with an industrial robot, skis and ski bindings are fixed to the force sensor and the robot repeats the movements of the shank relative to the skis. Therefore, measured trajectories formed by the marker positions have to be transformed to the coordinate system with the origin at the point m_1 and defined with marker points m_1, m_2 and m_3. Transformed coordinates were obtained using the following equations:

$$\vec{a} = \frac{\vec{m}_1 - \vec{m}_2}{\|\vec{m}_1 - \vec{m}_2\|},\ \vec{b} = \frac{\vec{m}_3 - \vec{m}_2}{\|\vec{m}_3 - \vec{m}_2\|},\ \vec{c} = \frac{\vec{a} \times \vec{b}}{\|\vec{a} \times \vec{b}\|},\ R = \left|\vec{a}\vec{b}\vec{c}\right|^T,\ \vec{m}_{R5} = R\vec{m}_5 \tag{1}$$

Vector $\vec{m}_{R5}$ denotes the transformed marker $\vec{m}_5$, which corresponds to the shank coordinates. Matrix R is the transformation matrix from the camera coordinate system to the ski coordinate system. Since $\left|\vec{a}\vec{b}\vec{c}\right|$ is a rotational matrix, it's inverse R can be obtained by matrix transpose. The robot can execute the trajectory composed from the series of $\vec{m}_{R5}$. The trajectory composed of the transformed shank positions is not very suitable for our purpose, since it's affected by the size of the shoes and the leg. A more suitable description of the trajectory is composed of shank angles, as illustrated in figure 2. The transformation from $\vec{m}_{R5} = (x, y, x)$ to leg angles $\varphi_1, \varphi_2, \varphi_3$ can be obtained using the following equations:

$$\varphi_2 = \arctan(\frac{y}{z}),\ w = \frac{z}{\cos(\varphi_2)},\ l_w = \sqrt{l_1^2 - h^2},\ \varphi_1 = \arccos(\frac{x^2 + w^2 - l_w^2 - l_2^2}{2 l_w l_2})$$

$$\varphi_3 = \frac{\pi}{2} - \arccos(\frac{x^2 + w^2 + l_w^2 - l_2^2}{2 l_w \sqrt{x^2 + w^2}}) - \arctan(\frac{h}{l_1}) \tag{2}$$

where φ_1 is the angle between the tibia and the z coordinate axis in the sagital plane, φ_3 is the angle between the foot and x axis in the sagital plane and φ_2 is the angle between the tibia and the z coordinate axis in the frontal plane. The above equations are singular for $\varphi_2 = \pi/2$, but this situation never occurs during the cross-country skiing. Angles $\varphi_1, \varphi_2, \varphi_3$ can be obtained also by placing markers at the end of the ski boot sole and at the middle of the ankle, but there are several disadvantages of doing so. First, the right position of the ankle is hard to obtain, Second, the marker placed at the ski boot sole is often hidden. In the case presented in figure 1, marker m_3 is not in the same plane as the markers m_1, m_2 and the skis. Therefore, the offset angle due to the marker placement was subtracted form the calculated angles φ_1 and φ_3. During the simulation of the cross-country skiing with an industrial robot, the robot and the tested ski boot form a closed kinematic chain. In the closed kinematic chain, very small changes in the position can cause large forces. Therefore, the robot has to control the contact forces. In our case, the contact forces were ground reaction forces, which had to be previously measured. We have measured ground reaction forces with our own developed system for ground reaction forces measurements in alpine and cross-country skiing (Nemec 97). The system consists of four load sensors per leg, inserted between the ski bindings and skis. Ground reaction forces were saved in the data logger with the sampling frequency of 100 Hz. The measurements were synchronised with the optical kinematic measurement system and with the camcorder (Kugovnik et al., 98). The system is capable of measuring the total ground reaction force in the *z* direction and the torque components M_x and M_y around *x* and *y*-axis respectively.

simulation of the cross country skiing with the industrial robot

In order to simulate the movements of the cross-county skiing, a robot with force, velocity and acceleration capability similar to those produced by the human shank is required. The robot has to have the possibility to track the arbitrary force and trajectory. The required working space is small compared to the typical working space of an industrial robot. In order to obtain the required capabilities we have developed a special 3-d.o.f manipulator. We have chosen the industrial Cartesian structure, AC servomotors with planetoid gears and belt transmission. The robot is presented in figure.4. The maximum velocity of the robot is 2 m/s and maximal payload is 1000 N. The robot is equipped with a force-torque sensor (JR3, model 45E15) with measuring capacity of 2000 N, 1000 N and 1000 N in the *z, x* and *y* direction respectively and 125 Nm about the *z, x* and *y* axis. For the simulation purpose, sole trajectory tracking is not sufficient. Small changes in the ski boot geometry such as ski-boot sole thickness can completely change the resulting force in the *z* direction. Therefore, the movement during the simulation *z* has to be force controlled. We have implemented the modified hybrid force-position control law, where force is controlled by position increments (Nemec, 92). The benefit of this control law is that it can be implemented on an existing robot controller without torque reference input. On the other hand, the gain of the force controller is affected by the environment stiffness (Nemec, 92b). In our case, the environment stiffness was changing according to the artificial leg position, which limits the performance of the robot at high-speed force tracking. We have solved this problem by implementing a two-phase simulation cycle. In the first phase, the movements were performed at low speed with the hybrid force control law. The achieved position trajectory was saved and used in the next cycle, where the robot controller was in the pure position mode. The trajectory obtained in the first cycle was velocity scaled in order to achieve the desired velocity. The artificial leg, used for tests of the ski boots, has 3 joints, as illustrated in figure 4. It is made of the aluminium joints and covered with rubber. The stiffness of the artificial leg joints can be changed using the reinforcement bars with the desired stiffness, which are inserted into the leg. The artificial leg was connected to the robot arm using a spherical joint.

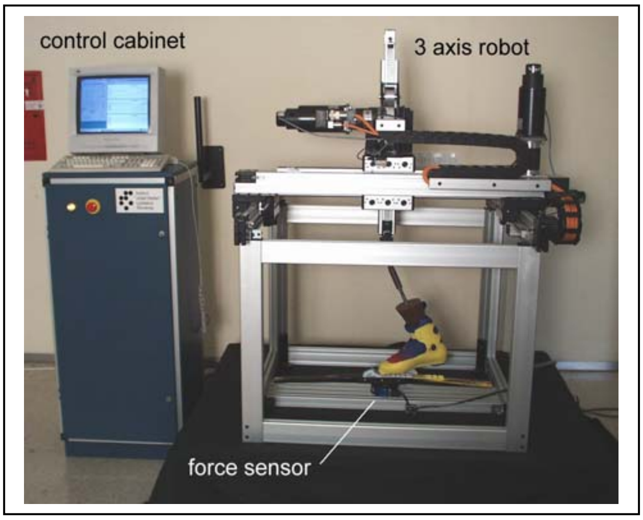

Figure 3 Robot for testing ski boots

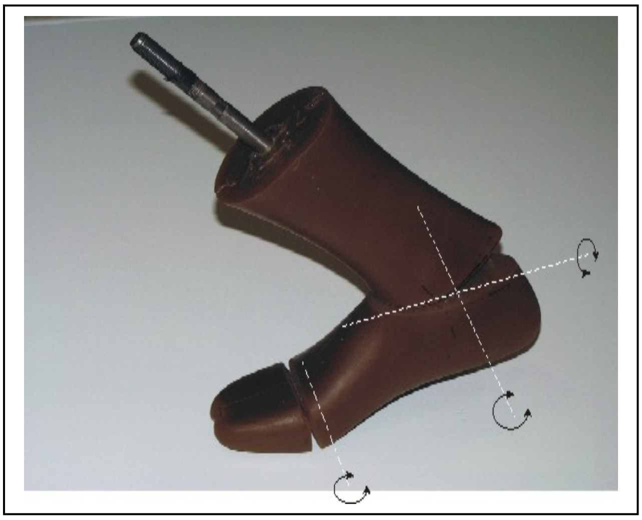

Figure 4 Artificial leg

RESULTS

We have measured the kinematics and ground reaction forces in cross country skiing for various snow conditions, flat and steep terrain and with classical and skating technique. The ground reaction forces were captured for both legs, while the kinematics data were taken from the left leg only. Measurements on the flat terrain were repeated indoors with inline skates. As expected, indoor measurements of the kinematics data were far more precise comparing to those of the outdoor measurements. The reason is the better resolution of the ELITE infrared measurements system and automatic digitalisation of the markers, which is much more precise and reliable comparing to the manual digitalisation required by the ARIEL measuring system. The measured marker coordinates in the camera coordinate system were transformed to the ski coordinate system using Eq. 1. The typical trajectory representing shank movement in the ski coordinates system for one ski step using skating technique is displayed in figure 5. The tester was an elite biathlon competitor, weight 67 kg, age 27. The trajectory was smoothed using a fifth-order Butterworth filter with frequency cut at 2 Hz. The corresponding measured ground reaction forces are shown in the figure 6.

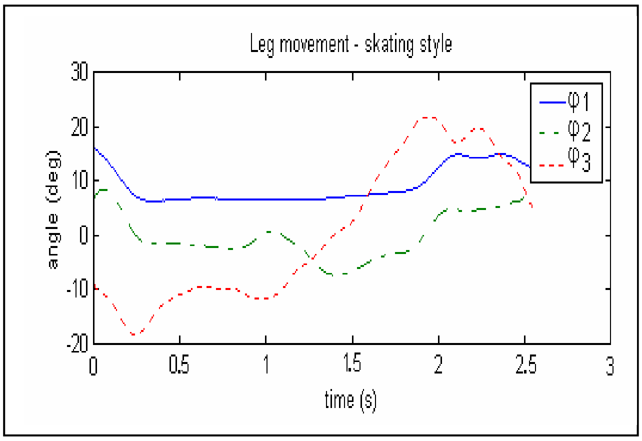

Figure 5 Shank movement of the left leg, skating style

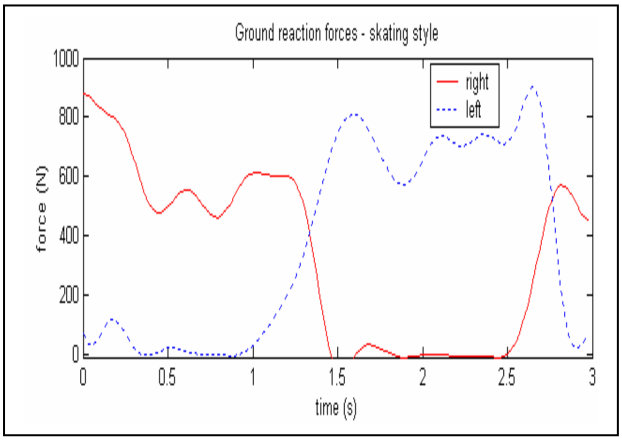

Figure 6 Ground reaction forces in z direction, skating style

To demonstrate the efficiency of the proposed method, two ski boots were compared. The first is a racing skate boot and the other is an all-round ski boot of intermediate quality. Both ski boots were tested using the same test trajectory. The ski boot temperature was 2 ^{0}C. In order to compare ski boots, we have to define the important parameters of the ski boots. The ski boots differ depending on the technique used. Here, ski boots are tested with skating technique. For the skating ski boot, two parameters are important – lateral stability around x axis and the torsion around z axis. That means, that the ski boot for skating technique should be rigid around x and z axis. These two as well as other 4 forces and torque were captured using a universal force-torque sensor (JR3, model 45E15) mounted under the ski. Therefore, ski bindings also affect the measurements and we have to compare different ski boots using the same bindings. Unfortunately, unlike in the alpine ski boots, there exist no universal bindings that would fit all ski boots. In the case of different ski bindings we have to be aware of the fact that we actually measure the behaviour of both ski boots and the ski bindings. Comparison between measured torque of the tested recreational and racing ski boots using the force and position trajectories of the left leg from Fig 5 and 6 are presented in figure 7. We can notice, that elite racing model is far more rigid and thus provides better support to the athlete. This information is valuable to the ski boot designer and extremely useful, when compared with the results obtained with various ski boot models.

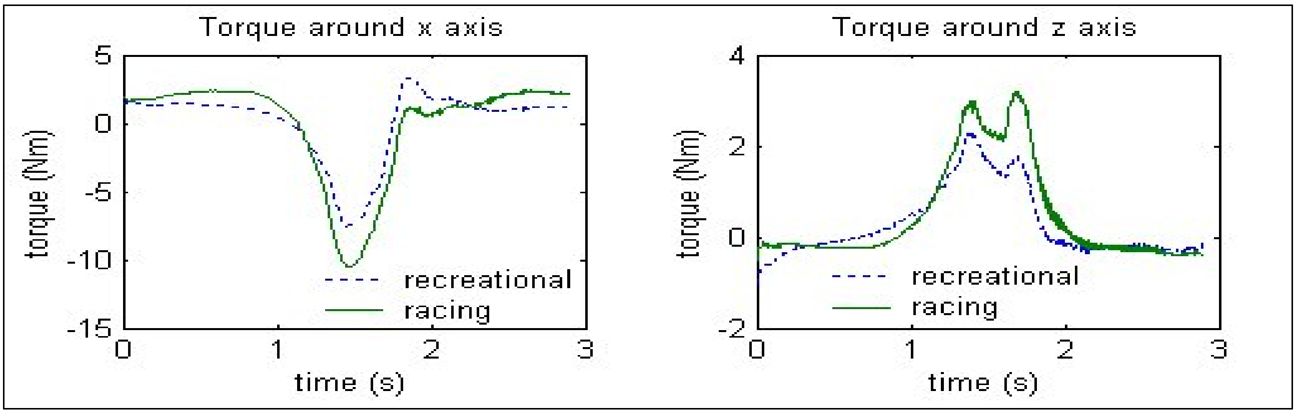

Figure 7 Comparison between toques measured on recreational and racing ski boot during the simulation with the robot

DISCUSSION

A new method for testing cross-country ski boots was presented. It consists of the measuring phase, where the movement and ground reaction forces of the sports activity are captured and the simulation phase, where the movement is repeated using an industrial robot. Since the subject temperature affect the measurement, the ski boots were previously cooled off to the desired temperature. The method was successfully applied for testing cross-country and alpine ski boots and with some modifications it can be used for other sports equipment testing such as ski bindings, skis, trekking shoes, etc. It was shown that the testing requires a force controlled robot, since the robot and the tested subject form a closed kinematic chain. Most of the measurement inaccuracies were due to the construction of the artificial leg. Currently, the artificial leg is a passive device with the possibility to change the stiffness of each joint. In order to simulate the behaviour of the human leg more precisely, an active device would be necessary. An active artificial leg should not be heavier than the human leg, which eliminates the usage of servomotors. Therefore, we are currently developing a new artificial leg with pneumatic muscles, which give a good torque-weight ratio.

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