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Short communication

Measuring spatio-temporal parameters of uphill ski-mountaineering with ski-fixed inertial sensors

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ABSTRACT

In this study an algorithm designed for the diagonal stride in classical cross-country skiing was adapted to compute spatio-temporal parameters for uphill ski mountaineering using a ski fixed inertial sensor. Cycle duration, thrust duration, cycle speed, cycle distance, elevation gain, and slope angle were computed and validated against a marker-based motion capture system during indoor treadmill skiing. Skiing movement of 12 experienced, recreational level athletes was measured for nine different speed and slope angle combinations. The accuracy (i.e. mean error) and precision (i.e. standard deviation of the error) were below 3 ms and 13 ms for the cycle duration and thrust duration, respectively. Accuracy (precision) for cycle speed, cycle distance and elevation gain were −0.013 m/s (0.032 m/s), −0.027 m (0.018 m), and 0.006 m (0.011 m), respectively. Slope angle accuracy and precision were 0.40° and 0.32°, respectively. If the cross-country skiing algorithm would be used without adaptations, errors would be up to one order of magnitude larger. The adapted algorithm proved valid for measuring spatio-temporal parameters for ski-mountaineering on treadmill. It is expected that the algorithm shows similar performance on snow.

1. Introduction

The movement of ski-mountaineering is similar to that of classical cross-country skiing. In contrast to cross-country skiing the slopes in ski-mountaineering are steeper, both uphill and downhill. Therefore, during climbing the skis are equipped with adhesive skins to prevent sliding backwards. Several studies investigated energy expenditure during ski-mountaineering races (Duc et al., 2011; Praz et al., 2014; Tosi et al., 2009, 2010). Energy expenditure was estimated from measured oxygen consumption (Duc et al., 2011; Tosi et al., 2009, 2010) or with a model estimating oxygen consumption from heart rate (Praz et al., 2014). Another study investigated exercise intensity based on heart rate (Schenk et al., 2011). These studies found that age, body mass, gear mass, aerobic capacity and efficiency were significantly correlated with climbing performance. However, it is unknown if certain biomechanics features are associated with performance. The objective of this study was to propose a ski-fixed inertial sensor system to automatically quantify spatio-temporal parameters of ski-mountaineering such as cadence, speed, and slope angle. Ski-mountaineering movement resembles the cross-country diagonal stride skiing movement but is slower, lacks the gliding phase and has a longer ski push duration. Thus, an algorithm designed originally for the diagonal stride of classical cross-country skiing (Fasel et al., 2015) was adapted to uphill ski-mountaineering to extract the relevant spatio-temporal parameters. The algorithm was validated against a 3D camera reference system while simulating ski-mountaineering with roller skis on a treadmill.

2. Methods

2.1. Protocol

The study protocol was approved by the Valais research ethics committee (CCVEM 033/11). Each participant gave informed written consent prior to participating to the study. 12 experienced, recreational level athletes were enrolled to the study. The measurement was performed indoor on a treadmill (Saturn 250/100, h/p/cosmos, Germany, belt dimension 250 cm × 100 cm) using cross-country forward only roller skis with bindings adapted for ski-mountaineering boots and normal ski-mountaineering poles fitted with a rubber stop at the extremity. Each athlete used their own, regular ski-mountaineering boots. A familiarization session a few days prior to data recording was organized for each athlete. After an individual warm-up each athlete performed the nine trials listed in Table 1 in randomized order. Each trial was performed for 3 minutes. No instructions were given according to skiing style.

2.2. Materials

A small inertial measurement unit (Physilog III, GaitUp SA, Switzerland) measuring 3D acceleration and angular velocity at 500 Hz was attached to the left ski, in front of the binding. Additionally, two reflective markers were placed on the ski

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Table 1
Measured skiing conditions, values as entered in the treadmill control computer. 5.71° corresponds to 10% inclination, 9.65° corresponds to 17% inclination, and 13.5° corresponds to 24% inclination.

Label	Slope	Speed
Flat, slow	5.71°	1.11 m/s
Flat, medium	5.71°	1.39 m/s
Flat, fast	5.71°	1.67 m/s
Medium, slow	9.65°	0.83 m/s
Medium, medium	9.65°	1.11 m/s
Medium, fast	9.65°	1.39 m/s
Steep, slow	13.5°	0.56 m/s
Steep, medium	13.5°	0.83 m/s
Steep, fast	13.5°	1.11 m/s

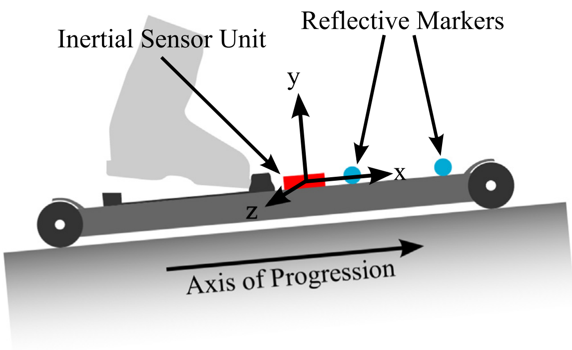

Fig. 1. Inertial measurement unit and reflective marker placement on the roller ski.

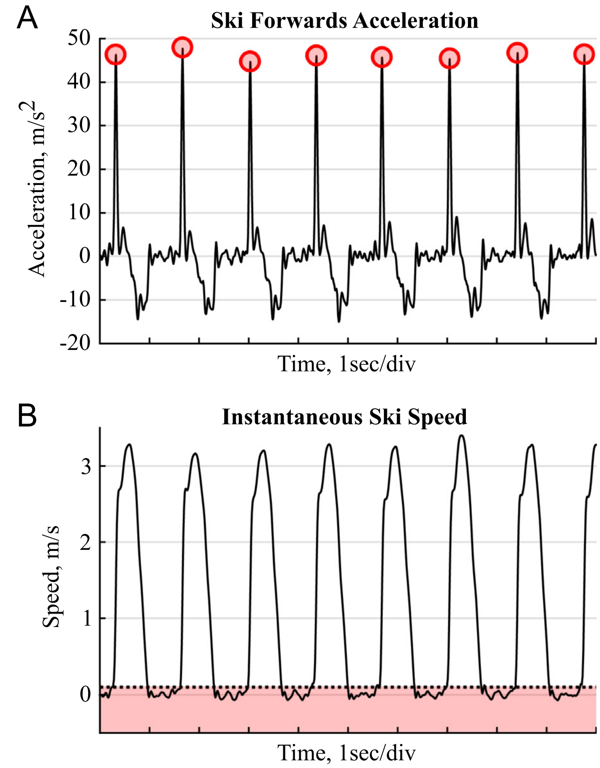

Fig. 2. Ski forward's acceleration and speed obtained from the inertial sensor. A) Example curve of the unfiltered ski forward's acceleration during 10 s of ski-mountaineering. The cycle starts are marked with the red circles. Phases of zero acceleration correspond to the ski thrust phases. B) Example curve of the ski forward's speed (same measurement as Fig. 2A). The threshold for motionless is marked with the dashed line. The phases where the ski speed is in the red zone correspond to the ski thrust phases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

aligned with its longitudinal axis (Fig. 1). The marker positions were recorded at a sampling rate of 200 Hz with an optical motion capture system consisting of seven infrared cameras positioned around the treadmill (Vicon Peak, Oxford, United Kingdom). The system was first calibrated and then electronically synchronized with the inertial measurement unit (IMU). Electronical synchronization was achieved by recording simultaneously a synchronization pulse by the Vicon system and the IMU system at the start and end of each trial. The time offset and sampling rate of both systems were then adjusted so that the synchronization pulses recorded on both systems matched perfectly.

2.3. *Definition of the parameters*

The ski thrust phase was defined as the phase during which the ski was flat on the treadmill, not moving (Fasel et al., 2015). A cycle was defined to start at the beginning of the ski thrust phase of the left leg and end at the beginning of the subsequent left ski thrust phase. Cycle speed was the average ski speed during one cycle. Cycle duration was the time difference between the two beginnings of the ski thrust phase. Cycle distance was the distance covered by the ski in one cycle. Elevation gain was the vertical elevation gain from one cycle and the slope angle was the inclination of the slope surface.

2.4. *Parameter computation with the inertial unit*

The algorithm described by Fasel et al. (2015) was adapted for the movement of ski-mountaineering. The difference with regard to the cross-country skiing algorithm (Fasel et al., 2015) was adapted motionless detection and drift correction, since in ski-mountaineering the thrust phase is considerably longer than in diagonal stride cross-country skiing. The motionless detection in the proposed algorithm was based only on a threshold in skiing velocity (see below), whereas in the cross-country skiing algorithm the acceleration was used as well for detecting the motionless phase. Furthermore, for the current algorithm only the central 50% of the motionless period was used to estimate the drift for both ski orientation and speed.

In short, the adapted algorithm works as follows: after functional calibration, ski inclination with respect to gravity was computed using trapezoidal integration of the ski's medio-lateral angular velocity. The orientation drift was corrected using samples from the central 50% of each motionless ski thrust phase, approximately estimated based on the criterion of locally minimal skiing speed detected in the drift- and gravity-affected speed estimate obtained by integration of ski's forward acceleration. Second, knowing the ski's orientation, the earth's gravity was removed from the measurements and the inertial acceleration along the longitudinal axis of the ski (Fig. 2A) was integrated to obtain the instantaneous skiing speed (Fig. 2B). Third, speed drift was corrected using the previously estimated motionless phases. Fourth, the ski thrust phases where improved using an empirically selected threshold of 0.1 m/s on the instantaneous ski speed (Fig. 2B). All samples below this speed threshold were considered as belonging to the ski thrust phase.

The slope angle was estimated as the average ski inclination during each ski thrust phase. Cycle speed was the average instantaneous ski speed over one cycle. For the purpose of robustness and precision, the start of a cycle was defined as the peak of the forward ski acceleration after each motionless phase (Fig. 2A). Cycle duration was the time difference between two consecutive cycle starts. Cycle distance was the product of cycle speed and cycle duration. The elevation gain was computed as the product between the cycle distance and the sinus of the slope angle.

For comparison purposes the original cross-country skiing algorithm published in (Fasel et al., 2015) was applied to the ski-mountaineering dataset as well.

2.5. *Reference parameter computation*

The reference parameters for cycle duration, thrust duration, cycle speed, cycle distance and elevation gain were computed based on the ski markers' speed as determined with the motion capture system using the same method as for the IMU. The marker speed was obtained through numerical differentiation of the marker positions. Details are provided in Fasel et al. (2015). The reference slope angle was directly obtained from the treadmill.

2.6. *Statistical analysis*

For each trial t, the cycle-by-cycle difference between the IMU-based parameters and the reference parameters was computed for all cycles of the trial. Next, the mean difference (μ_t) and standard deviation (std) of the difference (σ_t) was computed for each trial. The algorithm's accuracy was defined as the mean of all μ_t. The algorithm's precision was defined as the mean of all σ_t. Relative accuracy and precision were defined identically where the cycle-by-cycle difference was normalized by the reference parameter value prior to computing any mean or standard deviation. Error dependency on trial condition (speed and slope) was assessed using Pearson's correlation coefficient on the cycle-by-cycle data.