A NEW METHOD FOR UNCONSTRAINED MEASUREMENT OF KNEE JOINT ANGLE AND TIMING IN ALPINE SKIING : COMPARISON OF CROSSOVER AND CROSSUNDER TURNS

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Timing is an important part in the analysis of alpine skiing technique. Key events extracted from dynamics and kinematics of ski were previously proposed, but timing of body segments kinematics is also required to understand the biomechanics and to assess the performance. In this study, we proposed a new method based on inertial sensors to measure timing parameters based on body segments kinematics. To show the efficacy of the method, angle and timing of knee joints during crossover and crossunder techniques were compared. Significant differences were obtained for the timing, but not for the amplitude of the knee angles. The proposed system reported a good repeatability, did not encumber the athletes and allowed the measurement of body movement during the whole run. So it could easily be used to assess performance in training conditions.

KEY WORDS: Alpine skiing, inertial sensors, timing, knee angle, training conditions

INTRODUCTION: Measuring the timing of key events of alpine skiing technique (e.g., beginning or end of steering phase) is essential to understand the biomechanics and performance of this winter sport. For example, when comparing carving and traditional techniques, Müller & Schwameder (2003) noticed important differences in the timing periods of the initiation and steering phases. Currently, the key events timed in alpine skiing are based on the dynamics (Vodickova & Vaverka, 2009) or kinematics (Wägli et al., 2009) of the skis. Although crucial, these events are not sufficient for a complete characterization. In fact, it is also necessary to measure the key events of body segments kinematics.

Video camera is the common method for timing evaluation. According to Chardonnens et al. (2009), it is a precise measurement system (about two images or 8 ms with a standard 2D 25Hz camera). However, this method requires many manual operations and is therefore time consuming. Three-dimensional (3D) optical-based systems have also been used to quantify skier timing. Nevertheless, due to their technical complexity (e.g., small capture volume, requirement of professional staff for the setting-up and post-processing), these systems are limited to research studies. Consequently, there is a need for an easy-to-use timing system which can be directly used by trainers under in-field conditions. Wearable systems composed of inertial sensors were recently proposed as an alternative, suitable for routine evaluation. For alpine skiing, methods were proposed to measure body segment kinematics (Supej, 2009) and ski kinematics (Wägli et al., 2009). In addition, a system was presented to time temporal events during ski jumping (Aminian et al., 2009). Although promising, these methods require further improvement and validation.

The aim of this study was to propose an inertial-based method to automatically measure the relative knees joint angle and time particular events without limitation regarding the duration of the captures or their locations. In order to show the efficacy of the proposed method for alpine skiing, knee joint angular and timing parameters were defined and compared between crossover and crossunder techniques.

METHOD: A wearable system composed of four wireless inertial modules (Physilog®, BioAGM, CH), fixed laterally at the middle length of the thighs and behind ski boots, was designed to measure knee joints kinematics. Each module, weighting less than 100g, was composed of a 3D gyroscope (±1200 °/s), a 3D accelerometer (±10g) and an embedded datalogger recording the signals at 500 Hz. Before each run, a functional calibration procedure was performed to align the modules with the segments as proposed in Favre et al.

(2009). In order to evaluate the repeatability of the method, the inertial-based system was removed and replaced between each run (test-retest).

Six alpine skiers (27±4 years old, 180±5cm, 78±10kg), among which three were professional instructors and three were experienced skiers, took part in this study. They performed twice crossover (CO) and twice crossunder (CU) techniques on a regular slope (0.4km long, 100m large, 40% steep) with their own carving skis (13.5±0.8m radius; 166±8cm length). In addition, a standard video camera recording at 25Hz and synchronized with the proposed system was used to record the runs. Snow and weather conditions were similar for each skier.

The major difference between these two skiing techniques is that in CO technique, to edge from one side to the other during the initiation phase, the trunk swings over the lower limbs. On the contrary, in CU technique, the trunk remains stable and the lower limbs cause the change of edges. Based the knee joints function for these techniques, four events were defined for each turn as described in Table 1 and illustrated in Fig.1. These timing events were determined automatically for each turn using a robust detection method based on the differential sagittal angular velocity between thighs and shanks. The flexion-extension relative angles of knees modeled as a hinge joint were also calculated based on the angular velocities and accelerations measured by the four modules and by considering some joint and turn constraints (Bortz, 1971).

Table 1

Timing events definition from knee kinematics

BE	Beginning of the extension for the outer knee
BF	Beginning of the flexion for the inner knee
EE	End of the extension for the outer knee
EF	End of the flexion for the inner knee

In order to compare the two techniques, the range of knee flexion-extension, the absolute duration of the turn, as well as four intra-turn durations ($\Delta B = BF - BE$, $\Delta E = EF - EE$, $\Delta Ex = BE - BE$ and $\Delta Fl = EF - BF$) were calculated for each turn. The duration of the turn was defined as the time between two consecutive *BF*. The intra-turn timing periods were expressed both, as absolute values (in ms) and as percentage of the turn duration. The two first and last turns of the run were considered as transition phases and were therefore ignored in this analysis. Wilcoxon rank sum test was used to determine the level of significance of the differences observed between the two techniques. This test was done for the range of motion, the turn duration, as well as for the durations (expressed in ms and as percentage of the turn duration) considering all skiers and all turns of the two runs. The repeatability was assessed by Wilcoxon rank sum tests. In this case, the angular and timing parameters were compared between the first and second run. These tests were done separately for the CO and CU techniques, in each case considering all turns of the six skiers. An alpha value of 0.05 was considered to assess statistical significance.

RESULTS: An average of 11±4 turns per run was collected for each athlete. In total, the relative knee angles and the respective timing periods were calculated for more than 100 turns per technique. Typical results are presented for the CO and CU techniques in Fig.1.

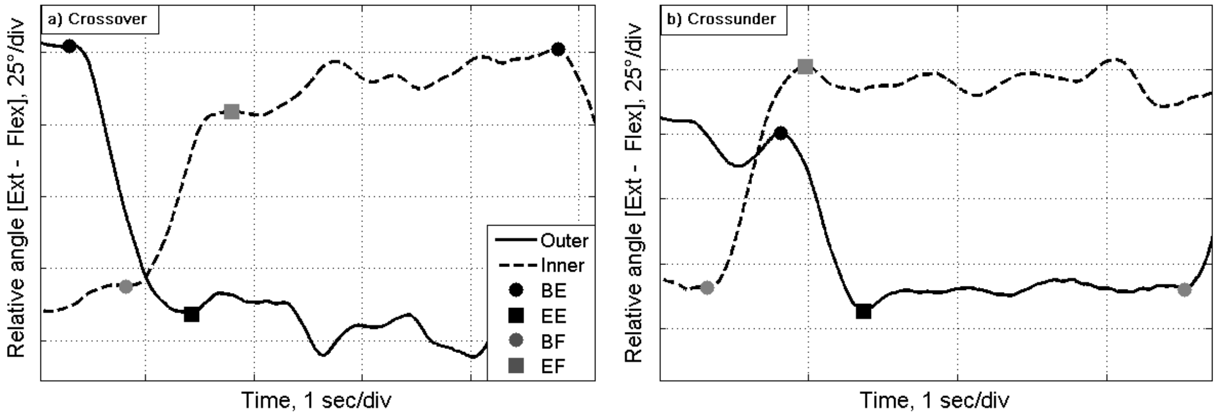

Figure 1: Typical relative knee flexion-extension angles and their temporal features a) crossover CO and b) crossunder CU techniques.

When comparing CO and CU techniques considering all turns, non significant differences were obtained for the range of motion and for the absolute timing periods. However, the timing periods expressed in percentage of the turn duration showed significant differences. Indeed, in this case, we found that ΔB and ΔE were significantly lower for CU than for CO. On the contrary, a significant increase was obtained between ΔEx and ΔFl when comparing CU to CO. Finally, although CU generally reported a longer turn duration than *CO*, this difference was not significant (p=0.07). The medians of the timing periods expressed as percentage of the turn duration are presented in Table 2.

Table 2

Medians in % of turn cycle for CO and CU

	ΔB	ΔE	ΔEx	ΔFl
CO	28	44	20	16
CU	-30	-34	50	70

The test-retest differences expressing the repeatability of the method were also not significant for the knee range of motion and all timing periods in ms and in percentage with the CU and CO techniques, except for ΔB in ms (p=0.03) with CU.

DISCUSSION: The wearable system presented in this study allowed the measurement of the relative knees angle and a robust detection of timing events based on 3D acceleration and 3D angular velocity measured at the thighs and boots level. It is worth mentioning that the angular and timing parameters were automatically calculated.

The proposed method was reliable on both CO and CU runs, since no significant changes were observed when the system was removed and replaced. Moreover, by showing significant differences between the timing periods of both techniques, this method showed a good efficiency to study skiing biomechanics.

It is interesting to note that significant differences of the timing periods between both techniques were only observed when the timing were expressed as percentage of the turn duration. This can be explained by the fact that the duration of the turn is different for each turn and by the fact that some temporal features are proportional to the turn duration. Therefore, by calculating their values as percentage of the turn duration, this proportionality was highlighted. In other words, this suggests that within each technique, the considered timing periods (ΔB, ΔE, ΔEx, ΔFl) are proportional to the turn duration and do not have an absolute constant duration.

Regarding the timing analysis of CU, we reported that the initiation of knee movement corresponded to the beginning of the outer leg knee flexion (*BF)*. The beginning of the extension movement (*BE)* appeared after *BF*, as illustrated in Table 2*.* Thus, no vertical movement of trunk was created. On the other hand for CO a positive *ΔB* was obtained, meaning that the movement was initiated by inner leg. The knee extension of the inner leg appeared before the flexion of outer leg, which induces a vertical displacement of trunk. A positive period ΔE for CO and negative for CU can be explained in the same way. Fig. 1 clearly illustrates this phenomenon.

Longer extension *ΔEx* and flexion *ΔFl* durations were reported for CU compared to CO technique (Table 1). This could be explained by the fact that swinging the legs under the trunk could require a larger percentage of the turn cycle than swinging the trunk over the legs, since lower limbs induce the entire movement. It is also important to note that CU is less commonly practiced than CO technique.

CONCLUSION: In this study, we proposed a new automatic method for the measurement of knee joint relative angles and timing periods based on inertial sensors. The proposed system did not encumber the subject and could easily be used during daily training. It allowed identifying relevant intra-turn parameters, as well as parameters relative to the whole run. The system showed a high sensitivity regarding the timing periods in term of percentage, as well as a good repeatability.

In addition, this study stressed the fact that relative angular amplitudes are not sufficient to characterize crossover and crossunder techniques. Indeed, significant differences between these techniques were only observed for relative timing durations. Although inertial sensors were sufficient to analyze the timing of knee, force and trajectory measurement could be added to complete the analysis. As skiing involves the movements of all body segments, other joints (e.g., hips) could also be considered in order to have a more general picture of the joint kinematics timing. Considering that the proposed method could easily be adapted for other joints, it was concluded that it has a high potential for daily monitoring of alpine skiing.

REFERENCES:

Aminian, K., Le Callennec, B. Cuendet, F., Chardonnens, J., Gremion, G. & Jolles, BM. (2009). Estimation of temporal parameters in ski jumps using wearable sensors*, In ISB*, Cape Town.

Bortz, J. (1971). A new mathematical formulation for strapdown Inertial navigation, *In IEEE Transaction on Aerospace and Electronic Systems*, 7(1), 61-6.

Favre, J., Aissaoui, R., Jolles, B. M., de Guise, J. A. & Aminian, K. (2009). Functional calibration procedure for 3D knee joint angle description using inertial sensors, *J. Biomechanics*, 42, 2330-5.

Chardonnens, J., Favre, J., Cattin, S., Jolles, B. M., Gremion, G. & Aminian, K. (2009). Evaluation of Errors in Alpine Skiing Video Analysis, In *ECSS*, Oslo, 131.

Müller, E., & Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping, *J. Sports Science,* 21, 679-92.

Supej, M. (2009). A step forward in 3D measurements in alpine skiing : a combination of an inertial suit and DGPS technology, In *Science and Skiing IV*, Meyer & Meyer Sport, Oxford, 497-504.

Vodickova, Ss. And Vaverka, F. (2009). The method of time analysis of a carving turn and its phaes, In *Science and Skiing IV*, Meyer & Meyer Sport, Oxford, 532-542.

Wägli, A., Meyer, F. Ducret, S., Skaloud, J. & Pesty, R. (2009), Assessment of timing and performance based on trajectories from low-cost GPS/INS positioning, In *Science and Skiing IV*, Meyer & Meyer Sport, Oxford, 556-564.

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