MORPHOLOGICAL ANALYSIS OF ACCELERATION SIGNALS IN CROSS-COUNTRY SKIING

Information extraction and technique transitions detection

Håvard Myklebust
Research centre for training and performance,
Norwegian school of sports sciences, Oslo, Norway
havard.myklebust@nih.no

Neuza Nunes
Physics Department, FCT-UNL, Lisbon, Portugal
neuzanunes@gmail.com

Jostein Hallén
Research centre for training and performance,
Norwegian school of sports sciences, Oslo, Norway
jostein.hallen@nih.no

Hugo Gamboa
Physics Department, FCT-UNL, Lisbon, Portugal
PLUX – Wireless Biosignals, Lisbon, Portugal
h.gamboa@fct.unl.pt, hgamboa@plux.info

Keywords: Cross-country skiing, accelerometers, expert-based classification, biosignals, signal-processing.

Abstract: **Aims**: Experience morphology of acceleration signals, extract useful information and classify time periods into defined techniques during cross-country skiing. **Method**: Three Norwegian cross-country skiers ski skated one lap in the 2011 world championship sprint track as fast as possible with 5 accelerometers attached to their body and equipment. Algorithms for detecting ski/pole hits and leaves and computing specific ski parameters like cycle times (CT), poling/pushing times (PT), recovery times (RT), symmetry between left and right side and technique transition times were developed based on thresholds and validated against video. **Results:** In stable and repeated techniques, pole hits/leaves and ski leaves were detected 99% correctly, while ski hits were more difficult to detect (77%). From these hit and leave values CT, PT, RT, symmetry and technique transitions were successfully calculated. **Conclusion:** Accelerometers can definitely contribute to biomechanical research in cross-country skiing and studies combining force, position and accelerometer data will probably be seen more frequently in the future.

1 INTRODUCTION

The increased numbers and decreased sizes of electronic devices is a major cause to the development of biomechanical research in real sports situations the last 15 years. In cross-country (XC) skiing research, different research groups have mounted small strain gauges into the poles and used commercial insoles for measuring forces from arms and legs of the skiers in addition to video recordings for quite some years (Millet et al. 1998, Holmberg et al. 2005, Stöggl et al. 2010). In addition to forces they often present parameters like cycle time (CT), poling/pushing time (PT), recovery time (RT) and figures showing timing of arms and legs (Lindinger et al. 2009). The strain gauges used, still have some limitations though. The weight and size of the equipment and the fact that skiers can not use their own poles makes data collection from competitions more difficult.

Skiers change between different types of techniques many times during a XC-skiing competition. It can be speculated if one technique is better than another in special types of terrain. We know there have been some coaches and researchers systematically looking at video and split times in different terrains, trying to understand what techniques are most efficient. Recently Anderson et al. (2010) presented a work in XC-skiing where a GPS were synchronised to video to get position and speed when the skiers changed technique.

In alpine skiing, Supej (2010) validated a system combining a suit with inertial sensors (accelerometers) and GPS for detecting body trajectory and segment movements. To our knowledge, accelerometers have not been used in XC-skiing.

The aims of this study were therefore to use accelerometers to extract cycle time (CT), poling/pushing time (PT), recovery time (RT) and symmetry between right and left side during XC-skiing using video recordings for validation. We also intended to develop an expert-based classification system which classifies the techniques used and detects the moments of technique transitions. This can help coaches and researchers in analysing the effect of different techniques in different tracks more effectively.

The following sections will describe our study and expose the results achieved. In section 2 we describe the acquisition scenario, the participants and apparatus used. In section 3 we expose the data analysis and processing, and how we acquire the necessary information from the accelerometers. Section 4 describes the procedure used to classify the cycles into techniques. Section 5, 6 and 7 presents the results, discussion and conclusion of our work, respectively.

2 MATERIALS AND METHODS

2.1 Overall study procedure

In this study, three XC-skiers finished the World Championship 2011 sprint event track (1480m) as fast as possible. They had accelerometers attached to their body and equipment, while two hand held cameras videotaped most of the track for validation.

The acquired data were analysed for the initiation (hit) and finalization (leave) events of skis and poles ground contact. The exact times when these events occurred were computed and validated against the video.

With these time points we were able to calculate CT, PT, RT and symmetry between right and left ski/pole. We also developed an expert-based system which classified the cycles of the accelerometer signals into defined skiing techniques, by fitting in the thresholds defined after signal analysis.

Because the World Cup was held this day, the snow conditions were optimal and we could get top level athletes to participate, but we could not standardize the start and end point of the track 100%.

2.2 Subjects

Three Norwegian male XC skiers, two 17 year old juniors and a 21 year old senior volunteered to participate in this study. The juniors (FP2 and FP3) are among the best in their age in Norway and the senior (FP1) were participating in the World Cup the day of testing. He volunteered to take a run with the accelerometers about one hour after he failed to qualify for the finals.

2.3 Techniques

The track used is designed in accordance to international regulations and made the skiers change between all normal skating techniques. We choose to name the techniques V1, V2, V3 and V0.

V1 is generally considered as an uphill technique and uses an asymmetrical and asynchronous pole push on one leg (strong side) but not on the other leg (weak side). This technique is also called “paddling”, “offset”, “gear 2” and other names in the literature. If the strong side is simultaneously with the right ski push we call the technique V1r and if the strong side is simultaneously with the left ski push we call the technique V1l.

V2 is usually viewed as a high speed technique used on flat terrain or moderate uphill. With this technique propulsive forces are symmetrically and synchronously applied during the ground contact of the poles for each skating push (both sides). Other names are “double dance”, “one skate” and gear 3.

V3 is used at even higher speeds on flat terrain. The technique is similar to V2 but the poles are only used on one side. Other names are “single dance” and gear 4.

V0 is here used for all other techniques including downhill, freeskate (just legs working) and turning techniques.

2.4 Apparatus and experimental design

To collect the acceleration data necessary for this study, five triaxial accelerometers, xyzPLUX (bioPLUX Research Manual, 2010), were used.

One accelerometer (ACG) was placed at the subject’s lower back on the lumbar region, near the centre of gravity. The default x axis of the accelerometer was orientated with positive values from left to the right, the default y axis were on the vertical direction, being positive from inferior-superior direction and the default z axis had positive values from posterior to anterior orientation. One accelerometer was attached to each pole just below the handgrip, and one accelerometer was attached at the heel of each ski-boot. The last four accelerometers were used as uniaxial accelerometers, as only one axis of the accelerometers (the one pointing upward in a neutral position) was connected to the acquiring system device.

To acquire and convert acceleration signals to digital data, a wireless acquisition system, bioPLUX research, was used. The system has a 12bit ADC with a sampling frequency of 1000Hz and the information is transmitted by Bluetooth at real-time. In this particular test a HTC mobile phone with Windows Mobile 6.1 received and stored the collected data for post processing, using an application, loggerPLUX, created for that purpose. (bioPLUX Research Manual, 2010)

3 DATA ANALYSIS

The data collected with the accelerometers was processed offline using Python with the numpy (T. Oliphant, 2006) and scipy (T. Oliphant, 2007) packages. Algorithms were developed to automatically perceive the initiation (hit) and finalization (leave) time of each ski and pole ground contact. For checking these time points against the video, Dartfish Connect 4.5.2.0 (Dartfish.com website, 2010) was used. Also, with this information, it was possible to compute CT, PT, RT, symmetry between right and left side, technique used and time points for technique transitions. Figure 1 summarizes the data analysis procedure that is minutely described foremost in this section.

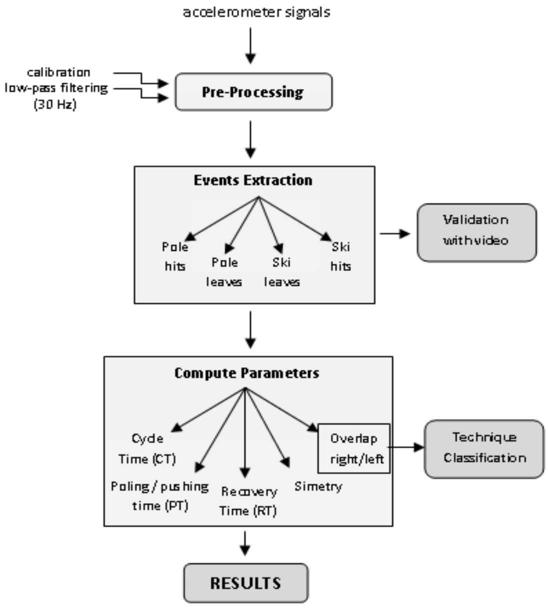

Figure 1: Schematics of the procedure.

3.1 Preliminary Processing

The primary procedure was to apply a low-pass filter with a cutting frequency of 30Hz to all signals.

We then converted the accelerometer data to G-units using calibration constants from each accelerometer. To get the calibration constants we acquired the rotation signal of the sensors through the 3 axes, so that acceleration on each axis ranged from -1g to +1g. The calibration constants are the maximum and minimum values on each axis. We get the mean value of these constants and with that information we can finally convert our acceleration data to G-units, applying the following formula:

$$\text{s\_cal} = (\text{s} - \text{mean\_cal}) / (\text{max\_cal} - \text{mean\_cal}) \tag{1}$$

with **s** being our acceleration signal, **max_cal** the maximum calibration constant, **mean_cal** the mean of the two calibration constants and **s_cal** our signal after the conversion.

For ACG we calculated the total acceleration from the following formula:

$$\text{a\_total} = \text{sqrt}((\text{a\_x})\text{^}2+(\text{a\_y})\text{^}2+(\text{a\_z})\text{^}2) \tag{2}$$

where a_x, a_y and a_z is the acceleration in the three directions.

3.2 Poles

The first data analysed were the signals from the right and left poles accelerometers. In order to get the moments when the pole hits and leaves the ground, we needed to exhaustively analyse the signal's behaviour and also its jerk and span signals (1^{st} and 2^{nd} derivative), so we could get the optimal thresholds for all the subjects.

In the next sections we will describe the procedure to differentiate the pole hits from the pole leaves.

3.2.1 Pole hits

By video and signal analysis we concluded that the pole hits happens near an inflexion point just after a minimum peak of the signal.

We took all the maximums of the jerk signal that were bigger than 0.035G/s and all the maximums of the span signal that were bigger than $0.0025G/s^2$ (optimal values we estimated after some analysis) and the pole hits were considered to be the samples giving the maximum jerk values that were close to (less than 50 samples apart) the maximum span signal. To eliminate some undesirable points, the events should correspond to a low signal value (less than -0.38G).

After this procedure there were still some extra poling hits mistakenly calculated, so we eliminate all the events that were less than 300 ms apart from each other. We also knew that left and right pole hits should be almost at the same time and eliminated the ones with a distance value bigger than 75ms.

3.2.2 Pole leaves

Analysing the video data synchronized with our signal, we concluded that the pole leaves happens near an inflexion point just before a maximum peak of the signal.

We therefore defined the pole leaves as the points were the maximums of the jerk signal were bigger than 0.04G/s, if that corresponded to a high signal value (more than 0.29G).

To eliminate some extra poling leaves mistakenly calculated, we eliminate all the events that were less than 300 ms apart from each other. We also knew that the left and right pole hits should be almost at the same time so we erased the ones with a distance value bigger than 100ms.

3.3 Skis

As the skis acceleration signals were very distinct from the poles acceleration signals, the processing used with the skis was somewhat different to the one used with the poles. For this part of the processing it was also necessary to analyse the signals with detail to get the optimal thresholds.

The procedure to get the ski hits and leaves will be described below.

3.2.1 Ski leaves

We began this part of the processing finding the maximum points of the ski signal that had a value bigger than 2.0G. However, with this approach some ski hit points were mistakenly confused as leave points. We then low pass filtered the acceleration signal with a smoothing average window of 500 samples and found the maximum peaks again but with a threshold of 1.323G. With this big smoothing window not all the peaks computed before met the required threshold value.

After that we compared the two peak results and we eliminated all the events that were more than 100ms apart, in other words, we erased some of the peaks encountered with the 2.0G threshold because they don't reach the 1.323G with a smoothing factor applied.

To eliminate some extra ski leave points, we eliminate all the events that were less than 200ms apart from each other.

3.3.2 Ski hits

For the ski hit events we only used the span signal of the left and right skis. We detect the minimum peaks that had a value lower than $-0.0045G/s^2$, and eliminate all the peaks that were less than 200 ms apart. To erase the downhill parts (undesirable because the skis don't leave the ground) we compared the skis leaves computed before with the skis hits and erased all the events that were more than 1300ms apart. We still had too many hit values compared with the leave ones, so we erased all the hits that were too close of the next leave (less than 250ms).

3.4 Skiing parameters

3.4.1 Cycle time, poling/pushing time and recovery time

From the hits/leaves for poles/skis we could calculate CT, PT and RT using these definitions:

(3) The cycle time (CT) is the time spent in each cycle. We consider that the beginning and ending of the cycle is a hit point. So, to compute the cycle times we get the distance values between all the hit events.

$$CT_i = hit_{i+1} - hit_i \tag{3}$$

Remark that calculating CT in V2 technique using pole hits require to use time between every other pole hit.

(4) Poling/pushing time (PT) is defined as the time spent with the ski or pole on the ground, the time between a hit and a leave. To compute these values, we subtract the hits events to the corresponding leaves points.

$$PT_i = leaves_i - hits_i \tag{4}$$

(5) The recovery time (RT) is the time which the subject spends takes to begin another cycle, after getting the ski or pole off the ground. That way this value can be defined as the cycle time minus the pulling time.

$$RT_i = CT_i - PT_i \tag{5}$$

3.4.2 Symmetry between right and left side

Another interesting variable is the symmetry between right and left side and if pole hits/leaves are synchronic or not. This was checked by subtracting hit, leave, CT, PT and RT calculated from right pole from the values calculated from the left pole. For example, for the poling/pushing times we did:

$$Sync\_PTpoles_i = PTleft\_pole_i - PTright\_pole_i \tag{6}$$

4 DATA CLASSIFICATION

The information gathered about the hitting and leaving timepoints from the ski and pole accelerometers were used also to classify the data into techniques.

For each pole hit we calculated two variables, one giving the time distance to the closest right ski leave ("overlap_right") and one giving the time distance to the closest left ski leave ("overlap_left"). Since this distances vary between techniques we could detect which technique each pole hit represented and from this also calculate the time points of the technique transitions.

Again, we had to analyse the overlap results for all the subjects in detail, to get the correct thresholds that separates and classifies our cycles correctly. The optimal thresholds were:

V1 right technique
$250 < overlap\_right < 500$
and
$-50 < overlap\_left < 200$

V1 left technique
$-150 < overlap\_right < 130$
and
$290 < overlap\_left < 575$

For V1 and V3 (see later) techniques it's also necessary that the previous or next cycle presents the same values for overlap_right and overlap_left.

V2 technique
As the V2 technique has a poling action for each ski push, there are two classifications possible with different thresholds.

Either:
$300 < overlap\_right < 600$
and
$-570 < overlap\_left < -250$.
And the previous or next cycle must be:
$-530 < overlap\_right < -250$
and
$300 < overlap\_left < 655$.

Or (switched around):
$-530 < overlap\_right < -250$
and
$300 < overlap\_left < 655$

and the previous or next cycle must be:

$$300 < overlap\_right < 600$$

and

$$-570 < overlap\_left < -250.$$

V3 right technique

$$-530 < overlap\_right < -250$$

and

$$300 < overlap\_left < 655$$

V3 left technique

$$300 < overlap\_right < 600$$

and

$$-570 < overlap\_left < -250$$

As for V1 technique, it is necessary that the previous or next cycle presents the same values for overlap_right and overlap_left.

Other techniques

All the other values that don't fit on any of the situations referenced above were classified as "other techniques" (V0).

5 RESULTS

5.1 Quality of our subjects

The junior skiers skied at a speed corresponding to 88% and 91% of the senior skier (FP1), respectively. When the senior skier skied for us he held a speed corresponding to 98% of the pace he used during the world cup event, which again corresponds to 97% of speed required to qualify for the finals in the world cup (less than 3 minutes).

5.2 Validity of hits and leaves

Our algorithm detected 99% of the pole hits and leaves correctly. For the ski leaves, 95-99% were detected correctly (Table 1), depending on if you look at all leaves in the track or only at parts of the track with stable technique (ST) over some time (only V1 or V2 in this samples).

For ski hits our code detected 77% correctly for ST. The problems of detecting hits were clearly greater in the V2 than in the V1 technique (Table 2).

5.3 Skiing parameters

5.3.1 Technique changes and % of time

Out of totally 67 technique transitions, our code made 8 mistakes, in other words 88% correct detection. The mistakes were 6 false transitions, 1 transition with wrong technique and 1 transition missing. Figure 2 shows the % of time in each technique based on the calculated technique time changes.

Table 1: Number of hits and leaves from poles and skis detected from video and % of correct detection from our algorithm. ST meaning stable techniques held over several cycles where in this case is only V1 and V2 techniques.

FP	Pole hits		Pole leaves		Ski leaves		
	N video	Correct (%)	N video	Correct (%)	N video	Correct (%)	Correct ST (%)
FPH	224	100.0%	224	100.0%	154	97.4%	99.4%
FPL	300	100.0%	296	100.0%	250	93.2%	98.8%
FPS	316	99.7%	282	99.6%	242	95.0%	99.2%
Total	840	99.9%	802	99.9%	646	95.2%	99.1%

Table 2: Number of ski hits analyzed from video (n) and correct detection from our code (%) subdivided into "all" (all techniques), "ST" ("stable techniques" held over several cycles, where in this case only V1 and V2 techniques), V1 and V2. Two hits per cycle were sometimes found in V2. The table shows how many of this 2.hit we found and how many % of correct detection our code gets if we assume that the 2.hit is wrong or correct.

FP	Ski hits						
		Correct				Correct V2	
	N video	All (%)	ST (%)	V1 (%)	N video	2 hit = wrong	2 hit = correct
FPH	172	67.0%	77%	97.0%	27	48.0%	85.0%
FPL	264	74.0%	86%	96.0%	14	71.0%	88.0%
FPS	251	59.0%	69%	95.0%	33	16.0%	63.0%
Total	687	67.0%	77%	96.0%	74	47.0%	57.0%

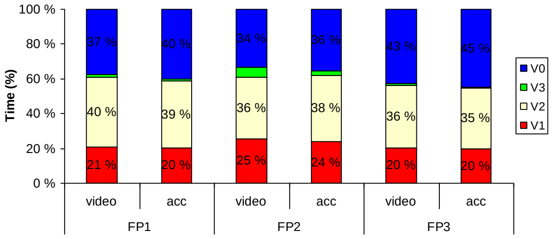

Figure 2: Relative time in each technique for each FP based on video analysis and accelerometer data (acc).

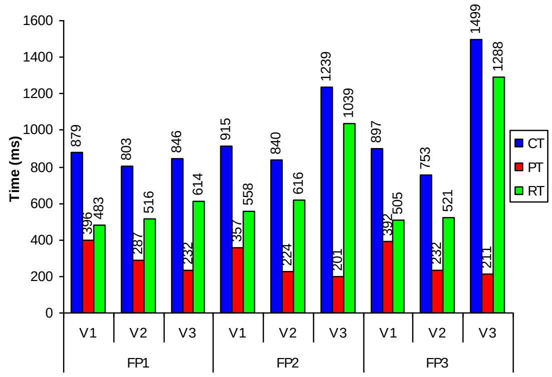

Figure 3: Mean CT, PT and RT for each technique and each FP based on right pole. Remark that CT, PT and RT for V2 will be twice as big for a complete cycle.

5.3.2 Cycle time, poling/pushing time, recovery time and timing of events

Differences between techniques were seen for CT, PT and RT (Figure 3). Figure 4 shows differences in timing of events between skiers in V1 technique and this can also be seen as differences between when poles and skis hits/leaves ground compared to centre of gravity total acceleration in the different skiers (Figure 5).

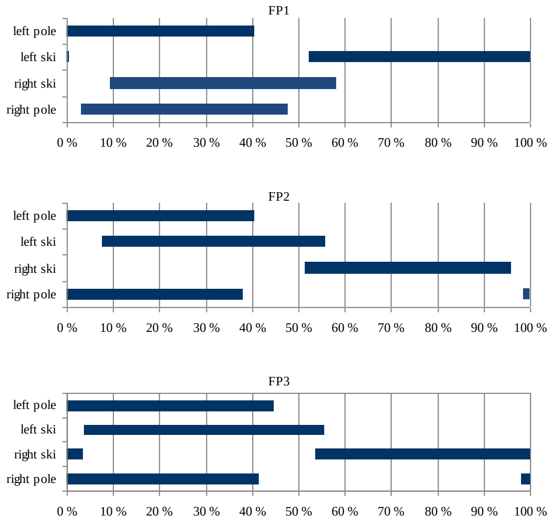

Figure 4: Cycle phase structure in V1 for the different subjects.

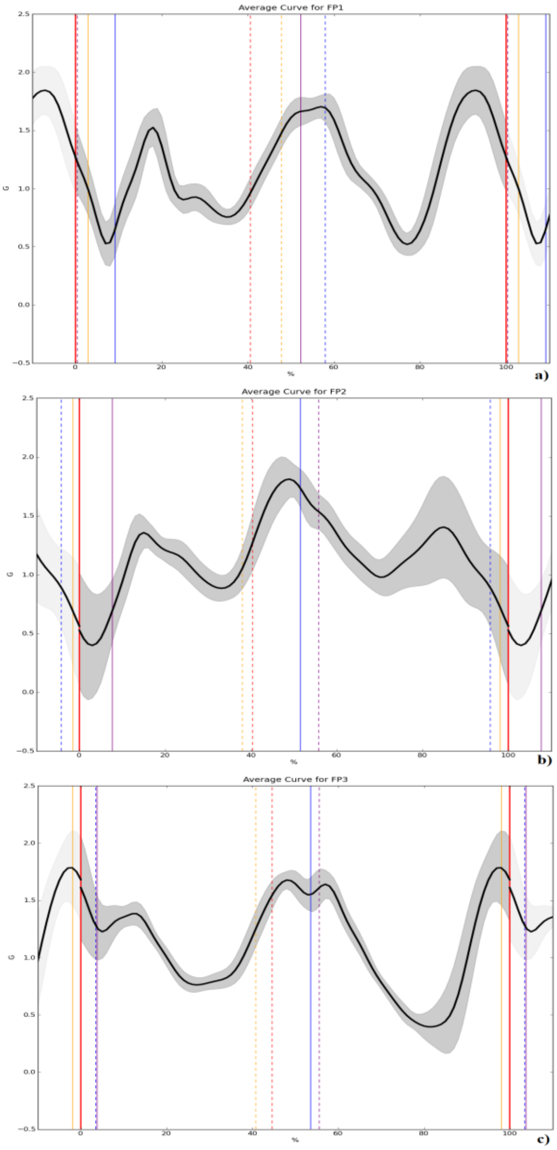

Figure 5: Average total acceleration from ACG during V1 technique. Time points for hits (solid lines) and leaves (dashed lines) of poles (orange = right, red = left) and skis (blue = right, purple = left), for FP1, FP2 and FP3 subjects (Figure 5 a), b) and c) respectively).

5.3.3 Symmetry between right and left side

FP1 had clear differences in symmetry between left and right pole in V1 compared to V2. This was not found in the other subjects, at least not in FP2 (Figure 6). Remark that FP1 used V1r (pole push simultaneous with right ski push) while FP2 and FP3 used V1l (pole push simultaneous with left ski push). FP1 did not ski the end of the track where there was a typically V1 uphill and the uphill he (and the others) skied was in a slightly right curve. Even though this might influence the data a bit, we also see that FP1 has less variation (smaller standard deviation) than the others indicating a more stable technique (Figure 6).

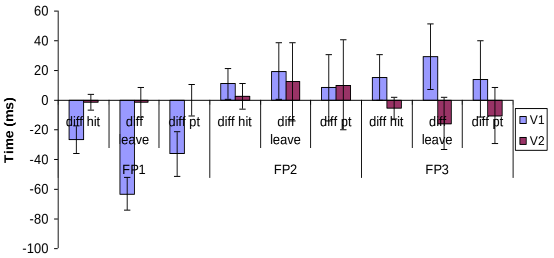

Figure 6: Time differences (Mean (SD)) in pole hit, pole leave and PT between left and right poles. Negative values for FP1 V1 mean that left pole hits the ground first, leaves the ground first and right pole has most time in the ground.

6 DISCUSSION

Our approach gave good results in the detection of pole hits/leaves and ski leaves. In addition to calculate CT, PT and RT previously only calculated when measuring forces (Stöggl 2010, Lindinger 2009), we were able to detect technique transitions.

Ski hits were more difficult to detect, especially in V2 because two hits sometimes showed up. This second hit results from a re-direction of the ski before the push off. Some skiers clearly use this newly developed “double-push” technique described by Stöggl (2008), and others (like our subjects) change technique over time using something in between of “double-push” and traditional V2. As the signals sometimes shows the second hit and other times doesn’t, and we are unsure if and when the second hit should be there and not, the worst results we get from the ski hits could be understood. This was also the reason why we did not present CT, PT and RT from the skis. We clearly have to either find a better approach or use strain gauges or pressure sensors for detecting ski hits. One approach might be to create a separate algorithm when the technique is classified as V2.

In addition to forces, strain gauges and force sensors can give the same timing parameters of hits and leaves as we have found with accelerometers, but we will point that the weight of equipment used for measuring forces are 3-5 times as high as our accelerometer equipment (1,5 kg vs. 300-500g. Stöggl 2010). We also think our equipment is easier to put on the skiers and the skiers can use their own poles. Even though we used accelerometers with cables into the wireless acquisition system in this study, there will shortly be devices available without need of cables. This will make the preparation even easier.

Combining different technologies like Supej (2010) have done in alpine skiing will probably be the future of biomechanical research. Accelerometer data from the area around centre of gravity or different limbs of the body in addition to force and positioning data will probably be useful during XC-skiing research.

7 CONCLUSIONS

Accelerometers were shown to be useful tools in XC skiing research. Accelerometers will probably be used more frequently in the future, in combination with force and positioning systems. Working with accelerometers can give insight in biological movement patterns and can give both solutions and ideas for more advanced biomechanical questions in the future.

FUTURE WORK

The thresholds used were fitted for these subjects and situation. Shortly, we will test the procedure on more data and different situations. We will try to improve our methods by finding the thresholds automatically and we will also check what information we can get from fewer accelerometers. The problems of finding ski hits obviously need more effort and we will continuously give feedback to the producers for developing even better equipment.

ACKNOWLEDGEMENTS

Thanks to the organising committee of the Holmenkollen 2010 World Cup for allowing our testing between the arrangement, and the subjects for participating on such short notice!

REFERENCES

Andersson, E., Supej, M., Sandbakk, Ø., Sperlich, B., Stöggl, T., Holmberg, HC., 2010. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol.* 2010 Jun 23 (Epub ahead of print)

Holmberg, HC., Lindinger, S., Stöggl, T., Eitzlmair, E., Müller, E., 2005. Biomechanical analysis of double poling in elite cross-country skiers. *MedSci in Spors & Exercise*, 37(5), 807-18.

Lindinger, S.J., Göpfert, C., Stöggl, T., Müller, E., Holmberg, HC., 2009. Biomechanical pole and leg characteristics during uphill diagonal roller skiing. *Sports Biomechanics,* 8(4), pp 318-333.

Millet, G.Y., Hoffman, M.D., Vandau, R.B., Clifford, P.S., 1998. Poling forces during roller skiing: effects of technique and speed. *Med Sci in Sports & Exercise,*30(11) pp 1645-1653.

PLUX – Wireless Biosignals, bioPLUX Research Manual, PLUX’s internal report, 2010.

Stöggl, T., Müller, E., Lindinger, S., 2008. Biomechanical comparison of the double-push technique and the conventional skate skiing technique in cross-country sprint skiing. *J Sports Sci.* 26(11), 1225-1233

Stöggl, T., Müller, E., Ainegren, M., Holmberg, HC., 2010. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sports*, 2010, 1-13.

Supej, M. 2010. 3D measurements of alpine skiing with an inerial sensor motion capture suit and GNSS RTK system. *J Sports Sci.* 28(7), 759-69.

T. Oliphant. Guide to Numpy. Tregol Publishing, 2006.

T. Oliphant. SciPy Tutorial. SciPy, http://www.scipy.org/SciPy Tutorial, 2007.

www.dartfish.com, 2010, last accessed on 19/07/2010