Håvard Myklebust

Quantification of movement patterns in cross-country skiing using inertial measurement units

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Summary

Inertial measurement units (IMU) are implemented in a variety of commonly-used technological equipment including cars and smartphones. IMUs are sensitive to motion, sample at high frequency, and have become small, wireless, and easy accessible at an affordable price. Hence, IMUs have been introduced as a tool for technique analysis in several sports. The overall aim of this thesis was to assess how, and to what extent, IMUs can contribute to technique analysis in cross-country skiing. Motion data were collected from up to five IMUs, which were mounted on a total of 28 skiers who skied using the V1 and V2 techniques. The most frequently reported technical variable in the literature, cycle time, was among the variables calculated from limb ground-contact temporal patterns. Additionally, three-dimensional hip acceleration, speed, displacement, and rotation were quantified during roller skiing on a treadmill, outdoor roller-skiing on asphalt, and on-snow skiing. This thesis is based on four papers, of which the first two focus on the reproducibility and validity of IMU data during ski skating, while the other two are more applicable to skiers and coaches.

Using IMUs allowed for easy data collection, and revealed highly detailed and reproducible movement patterns in all four studies. Limb-mounted IMUs provided a precise and simple way to perform ground-contact temporal analyses, except for estimating the timing of ski plants. For hip movements, the accuracy and precision of measurements (external validity) increased when accelerometer and gyroscope data were combined. Sideways center-of-mass displacement was accurately estimated by hip displacement, but there were large deviations in the vertical and antero-posterior directions. These systematic deviations between hip and center-of-mass movements were caused by arm and upper-body movements, which may be adjusted for.

Hip movement patterns captured by IMUs differed systematically between the V1 and V2 sub-techniques. V2 showed a similarity to double poling in terms of hip lowering during poling. This allows potential energy gained prior to the poling thrust to be transferred to propulsion through the arms and poles. Further, there were distinct differences between skiers using the same sub-technique, but movement patterns were consistent for individual skiers. IMU data quantified essential V2 technique alterations affecting work economy and performance in elite skiers. Small likely effects on performance were found for both cycle time (more precisely poling time and pure glide time) and vertical acceleration. When directly comparing on-snow skiing and roller skiing, altered hip rotation patterns, greater lateral displacement, longer poling times, and a tendency to smoother hip movements were found for on-snow skiing. The results indicate that different mechanical properties of the skis (not rolling/gliding friction) and/or surface hardness affect the V2 skating technique.

Samandrag

Både bilar og smarttelefonar inneheld sensorar som er følsame for bevegelsar. Slike bevegelsessensorar (IMU-ar) kan samle data med høg oppløysing, og sensorane er i dag små, trådlause, og forholdsvis rimelege. Dei seinare åra er derfor slike sensorar tekne i bruk for å samle data til teknikkanalysar i ulike idrettar. Målet for denne avhandlinga var å vurdere korleis, og i kva grad, slike sensorar kan nyttast for teknikkanalyse i langrenn. Bevegelsesdata frå inntil fem IMU-ar vart samla inn frå til saman 28 skiløparar. Opptak vart tekne når løparane skøyta med både padling og dobbeldans. Syklustid, den oftast rapporterte tekniske variabelen i litteraturen, var blant dei kalkulerte variablane frå ski og stavar si kontakttid med underlaget. I tillegg vart hofte akselerasjon, fart, forflytting, og rotasjon registrert tredimensjonalt både på tredemølle, ute på asfalt, og på snø. Denne avhandlinga byggjer på to artiklar med eit primært metodisk fokus på reproduserbarheit og validitet, samt to andre artiklane der funna har større nytteverdi for trenarar og løparar.

Å samle IMU-data var enkelt. Målingane var reproduserbare, og dei gav høg grad av nøyaktigheit i alle fire studia. Frekvens og kontakttid med underlaget kunne enkelt og nøyaktig bereknast med IMU-data frå stavar og skisko, men det var nokre utfordringar knytt til ski nedsett. Vi nytta sensorar som registrerte lineær akselerasjon (akselerometer) og sensorar som registrerte både akselerasjon og rotasjonshastigheit (gyroskop). Validiteten av målingane auka klart når akselerometer og gyroskop data vart kombinert. Vidare kunne sidevegs forflytting av kroppen sitt tyngdepunkt nøyaktig bereknast frå hoftebevegelsar i både padling og dobbeldans. Forskjellen mellom hofta og tyngdepunktet sine bevegelsar var derimot større i vertikal og framover-bakover retning. Dette kjem av korleis overkropp og armar vert nytta på ski, og mykje av forskjellen kan truleg korrigerast for.

Hoftebevegelsane i padling (V1) skilte seg klart frå dobbeldans (V2). Dobbeldans har bevegelsesmønster som liknar på staking med tanke på korleis tyngdepunktet vert heva før stavtaket og senka gjennom stavtaket. Det var og klare forskjellar mellom løparar som utførte same delteknikk, men kvar løpar gjentok sitt eige mønster. For fyrste gong vart det vist ein liten prestasjonsfremmande effekt ved å redusere frekvensen (auke sykluslengda) på individnivå. Ein tilsvarande effekt vart funne ved å redusere den vertikale akselerasjonen, spesielt når løparane glei på ei ski. Dette viser at betre dynamisk balanse er viktig, sjølv for eliteløparar. Sist men ikkje minst vart det vist at teknikken i dobbeldans på snø skil seg frå teknikken på rulleski. På snø roterte løparane hofta meir og annleis, dei gjekk breiare, hadde lengre kontakttid med stavane og vi fann ein tendens til at løparane gjekk med "mjukare" bevegelsar på snø. Forskjellen kom ikkje av ulik rulle/glid friksjon, men må skuldast at andre mekaniske forskjellar ved skia og/eller underlaget påverkar løparane sin dobbeldansteknikk.

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I came to NSSS in August 2002, only for a year... I want to offer my thanks to study friends, lecturers, researchers, students and administrators on all levels, including staff in the library, Servicetorget, Studieavdelingen, Cleaners, Drift, IKT, and anyone else contributing to making NSSS what it is. Especially, thanks for professional support and good memories to all my colleagues and friends in the department, including past and present PhD students, research assistants, engineers (Bjarne, Vidar, and Svein), and our office manager (Beate). Thanks also to Jan Cabri, head of the department at the time, for helping me return to NSSS in August 2012 after I had left for a period.

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Oslo, May 2016 Håvard Myklebust

Abbreviations and definitions

cm	Centimeters
COM	Center of mass
Cycle frequency	Number of cycles per second
Cycle length	Forward displacement during one cycle
Cycle time	Duration of a full cycle
Feature	A distinctive attribute
FIS	Federation of International Skiing
Gliding time	Duration of ground contact by the ski
GNSS	Global navigational satellite system
IMU	Inertial measurement unit
Inertia	Resistance to change of motion
Inertial sensor	A sensor based on the principle of inertia
Kick phase	Period between pole and ski liftoffs in V2
Kinematic analysis	Analysis of bodies in motion, without reference to what caused the motion
Kinetic analysis	Analysis of what causes motion (analysis of forces)
Longitudinal	Occurring over a period of time
mm	Millimeters
O_2-cost	Oxygen cost; Oxygen consumption at submaximal intensities
Pole liftoff	First time point without ground contact for the pole
Pole plant	First time point of ground contact for the pole
Poling	Period of ground contact for the pole
Pure glide	Period of ground contact for one ski only
Reposition time	Duration of period without ground contact for pole or ski, respectively
RMS	Root mean squared
Ski liftoff	First time point without ground contact for the ski
Ski plant	First time point of ground contact for the ski
SD	Standard deviation
S1	Os sacrum first vertebra; lower back
Technique	How a certain task is performed; specific sequence of movements
α	Arbitrary angle; alpha
Δ	Delta; change; difference
μ	Friction coefficient
°	Degrees
$\geq$ $>$ $<$	Larger than or equal to; larger than; smaller than

List of papers

I. Myklebust H., Losnegard T., Hallén J. Differences in V1 and V2 ski skating techniques described by accelerometers. *Scand J Med Sci Sports* 2014: 24: 882–893.

II. Myklebust H., Gløersen Ø., Hallén J. Validity of Ski Skating Center-of-Mass Displacement Measured by a Single Inertial Measurement Unit. *J Appl Biomech* 2015: 31: 492–498.

III. Losnegard T., Myklebust H., Ehrhardt A., Hallén J. Kinematical analysis of the V2 ski skating technique: a longitudinal study. *Under revision in Journal of Sports Sciences.*

IV. Myklebust H., Losnegard T., Hallén J. Kinematic differences between treadmill, asphalt, and on-snow ski skating. *Submitted*

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1.0 Introduction

The skating revolution in the 1980s showed clear evidence that technique—"specific sequence of movements" (Lees, 2002)—has a large effect on performance in cross-country skiing (Smith, 2003; Bolger et al., 2015). The aim in technique analysis is to understand what factors affect movement and how performance can be enhanced (Lees, 2002). Since a 0.3% performance enhancement is worthwhile and may make the difference between success and failure for elite skiers (Spencer et al., 2014), even small alterations in technique may be crucial.

The technique analysis methods used define opportunities and limitations. Historical methods range from 2D video analysis to combining whole-body 3D kinematics, kinetics, and muscle activation. The main drawbacks have been limited capture volume, interference with the skier's natural movement pattern, and the increased demands of in-field compared to laboratory measurement. However, today, low-cost inertial measurement units (IMU) are implemented in a variety of popular devices including smartphones, bracelets, and watches. Hence, IMUs are small, wireless, and easily accessible. They are easy to set up for data collection and sensitive to motion. They have a high sampling frequency and are thus promising for outdoor and ambulatory monitoring (Aminian & Najafi, 2004; Kavanagh & Menz, 2008). Therefore, IMUs have been introduced as a new tool for technique analysis in sports.

At first, IMUs only included accelerometers and were frequently used for gait analysis, to calculate number of steps and temporal patterns of ground contact (Kavanagh & Menz, 2008). Today, several units are sometimes combined, and each unit can include accelerometers, gyroscopes, and other sensors. For example, two IMUs combining accelerometer and gyroscope data were found promising for calculating knee joint angles (Favre et al., 2009), and a suite including 16 units was used to capture full-body kinematics in alpine skiing (Supej, 2010).

However, technique analysis methods should preferably be simple enough to be used by coaches and athletes in daily training. Center-of-mass (COM) acceleration reflects the product of all forces acting on the athlete, and a single IMU located on the lower back has been shown to provide valid estimations of COM displacement during walking (Floor-Westerdijk et al., 2012). Hence, an IMU estimating COM-displacement during cross-country skiing could be a useful tool for skiers and coaches. Since 2010, four other research groups have published papers using IMUs in cross-country skiing (Stöggl et al., 2014; Marsland et al., 2015; Fasel et al., 2015; Sakurai et al., 2016). However, the technique is new and has not yet been fully investigated. The purpose of this thesis was to assess how, and to what extent, IMUs can contribute to technique analysis in cross country ski-skating.

2.0 Background

2.1 Cross-country skiing and research

Cross-country skiing is an endurance sport in which performance is heavily dependent on the athlete's physiological capacities (Ingjer, 1991; Vesterinen et al., 2009; Sandbakk et al., 2011). In the Winter Olympics, competitions involve either individual or mass starts, and a large range of distances (1.2 – 50 km). The different tracks and distances require different degrees of anaerobic capacity and aerobic power (Losnegard et al., 2012a). Further, the upright position, combined with whole-body work in cold environments, often at moderate altitudes, is of interest to researchers in the field of sports physiology (Holmberg, 2015). Of the available cross-country skiing studies, Lindinger (2007) reported that only 11% were biomechanical studies, and only 4% combined biomechanics and physiology. However, historically, increased racing speeds have not been related to physiological development but rather to better track preparation and ski equipment (Holmberg, 2015). For example, the introduction of fiberglass skis in the 1970s reduced ski-snow friction and increased skiing speed (Smith, 1990). This, along with mechanical snow grooming, led to the skating technique revolution in the 1980s, with skating resulting in 12% – 15% higher average uphill skiing speeds compared to the classic technique (Bolger et al., 2015). This indicates the potential impact of technique on cross-country skiing performance.

2.2 Technique analysis

Technique is defined as *a specific sequence of movements* (Lees, 2002), or *how a certain task is performed*. The overall task for elite skiers is to achieve the highest *average speed*, or fastest *time* over a given distance. Competition tracks consist of a variety of different terrains, often divided into uphill, flat, downhill, and turn sections (Andersson et al., 2010; Sandbakk et al., 2011; Bolger et al., 2015). The terrain influences how gravity affects the skier's speed, and speed directly affects technique by altering the maximum time available for static ground friction (see section 2.2.1; e.g. Stöggl et al., 2011). Speed also affects the amount and the relative influence of air resistance (Svensson, 1994). Ski properties and snow/weather conditions also affect ski-snow frictional forces (e.g Breitschädel et al., 2012; Puukilainen et al., 2013). Additionally, tactics in mass-starts differ considerably from those used in individual starts. Hence, cross-country skiing involves many factors, resulting in a large number of "tasks", all of which can influence performance.

Aside from restricting sideways push on gliding skis in *classic* competitions, there are no competition regulations relating to technique. Hence, skiers have considerable degrees of freedom to optimize their technique to each specialized task. *Section-time analyses* show that specific techniques are normally used for specific terrains (e.g. Andersson et al., 2010). Classification of these sub-techniques is based on visually distinct differences in pole and ski ground contact times, known as *temporal analysis* (Figure 2.1; e.g. Nilsson et al., 2004). Skiers perform around 30 transitions between the six defined sub-techniques within a sprint race (Andersson et al., 2010). The factors affecting the choice of sub-technique and modification of movements are shown in Figure 2.2.

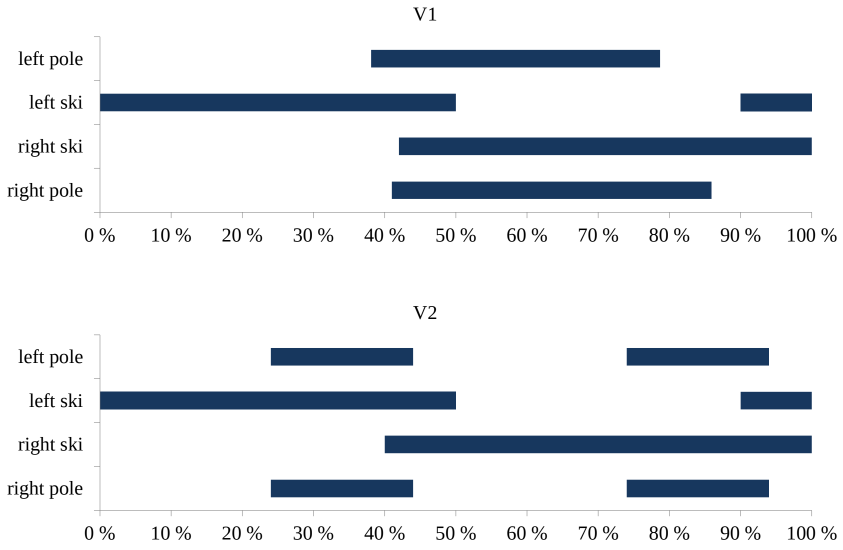

Figure 2.1. Temporal pattern of a normalized cycle, starting at right ski liftoff, in V1 (top) and V2 (bottom) for one skier. Bars indicate ground contact.

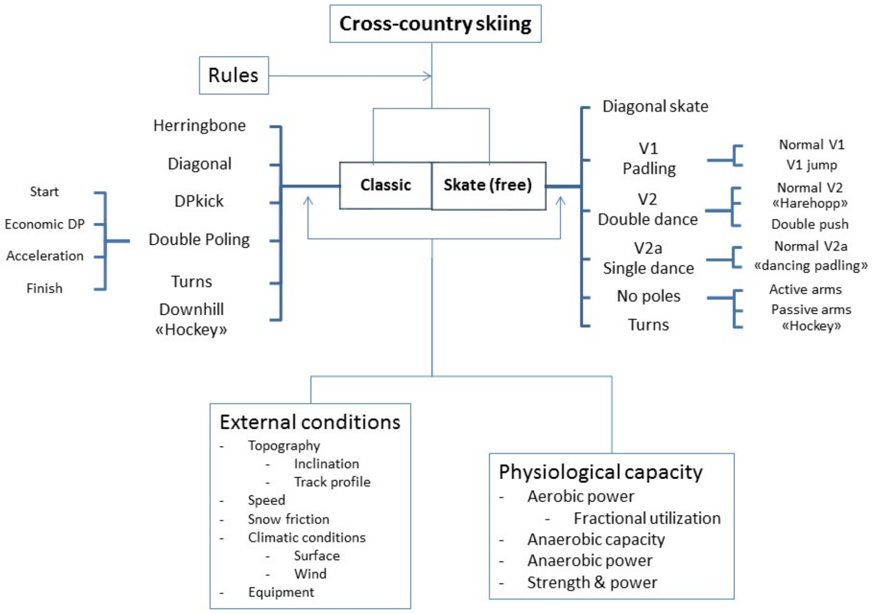

Figure 2.2. Sub-techniques and factors affecting choice of sub-technique.

2.2.1 External conditions and specificity

It is well documented that changes in external conditions (speed, inclination, and friction) influence skiers' technique. For example, temporal data show that all skiers increase cycle frequency as speed, inclination, or friction increase in double poling, V1, and V2 (e.g. Millet et al., 1998c; Stöggl & Müller, 2009; Losnegard et al., 2012b; Sandbakk et al., 2012a; Nilsson et al., 2013). However, speed, inclination, and friction affect technique differently. Both friction and inclination affect frequency only through reduced pole reposition time, while speed also affects poling time directly (Millet et al., 1998c; Sandbakk et al., 2012a; Othonen et al., 2013b; Nilsson et al., 2013). These findings show that standardizing external conditions is important, especially when comparing homogeneous groups of skiers or within-skier alterations.

Asphalt roller-skiing is the primary sport-specific training mode for elite skiers' summer training (Losnegard et al., 2013; Sandbakk & Holmberg 2014). Further, about 70% of biomechanical skiing research published in the last decade has used results obtained on a roller-skiing treadmill (e.g. Kvamme et al., 2005; Ainegren et al., 2009; Stöggl & Müller, 2009; Losnegard et al., 2013; Leirdal et al., 2013; Grasaas et al., 2014; Sandbakk et al., 2015; Stöggl & Holmberg, 2015). The main argument for using roller-skiing in a laboratory setting is to control external factors such as speed, inclination, friction, and weather conditions (e.g. Hoffman et al., 1994). Strong correlations have been found between treadmill roller-ski testing and on-snow skiing performance (Mahood et al., 2001; Sandbakk et al., 2011; Losnegard et al., 2013), and more advanced measurements can be performed more easily in a laboratory. However, several studies have noted that potential differences between roller-skiing and on-snow skiing techniques should be considered when interpreting research findings (Hoffman et al., 1994; Lindinger et al., 2009; Losnegard et al., 2012b; Sandbakk et al., 2012a). Treadmill roller-skiing does not include air resistance, and the ground surface and skis used are clearly different (Baumann, 1985). The marathon skate technique, which is not in use today, is the only skating technique that has been compared on roller-skis and on-snow skis (Gervais & Wronko, 1988). Treadmill roller-ski skating technique has not been directly compared to on-snow skating technique in any paper published in scientific journals.

2.2.2 Examined sub-techniques

Time spent in uphill skiing correlates best with sprint prolog performance (Andersson et al., 2010; Sandbakk et al., 2011). This might be due to different physiological capacities between skiers. However, a technique leading to reduced energy cost is assumed to improve performance (Losnegard et al., 2012b). Since the largest portion of time is spent in uphill sections during competition (Andersson et al., 2010; Sandbakk et al., 2011; Bolger et al., 2015), it is reasonable to assume that improved uphill technique will improve performance.

The papers included in this thesis focus on ski skating. The two techniques mainly used on moderate uphill terrain are the V1 technique (also named: “paddle dance”, “offset”, or “gear 2”) and the V2 technique (also named: “double dance”, “one skate”, or “gear 3”). The V1 technique is generally regarded as an uphill technique characterized by asymmetrical use of the upper body in one asynchronous double-poling action per cycle, timed with one of the ski pushoffs (Figure 2.3). In contrast, the V2 technique is seen as a "high speed" technique, and it is symmetrical in that there is one synchronous double-poling action with each ski pushoff (Figure 2.3). As the average speed in World Cup races has increased markedly over the last two decades (Losnegard et al., 2013; Sandbakk & Holmberg, 2014), the V2 technique has become the most commonly used technique in today’s race events (Andersson et al., 2010; Sandbakk et al., 2011). Hence, the V2 technique is the primary focus of this thesis.

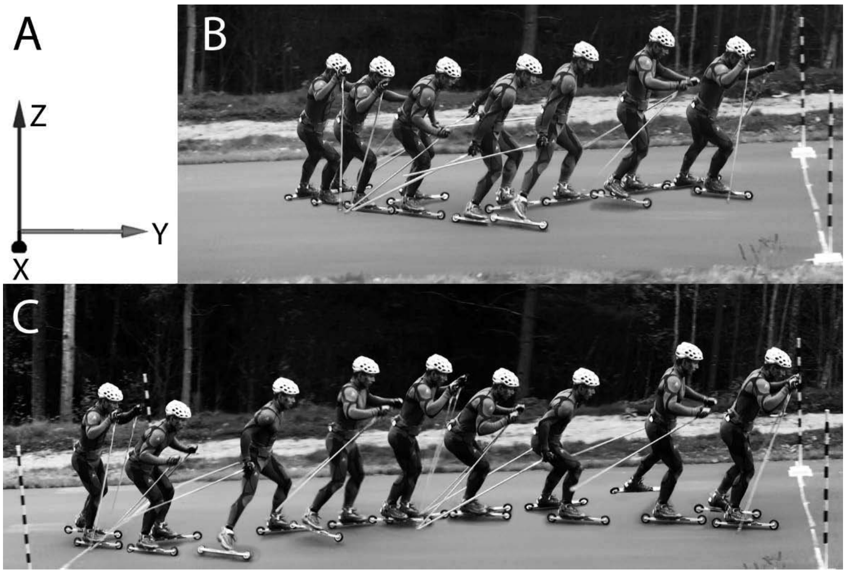

Figure 2.3. One full cycle of the V1 (B) and the V2 (C) techniques. The reference coordinate frame (XYZ) was defined from left to right, forwards, and upwards with XY as the horizontal plane (A).

2.2.3 Better skiers—better technique?

Technique must be quantified in such a way that objective comparisons between situations or athletes are possible. The level of sensitivity, accuracy, and precision needed, depends on the aim of the analysis. The sub-techniques are cyclic movements and the most frequently reported biomechanical variables are cycle length and cycle frequency. These variables are easily understood from a practical point of view, and cycle length is considered important since higher-ranked skiers use a longer cycle length both in double poling and V2 skating (e.g. Sandbakk et al., 2010; Stöggl & Holmberg, 2011). However, although better technique is believed to improve performance, it is not true that better performance indicates better technique (Lees, 2002). Losnegard et al. (2012b) showed that within a group of elite skiers the cycle length in V2 ranged from 5.0 – 7.5 m at a submaximal intensity with fixed inclination and speed. In addition, male elite skiers have longer cycle lengths and ski faster than female elite skiers. Even so, their gross efficiency has not been found to differ when matched against FIS rank points (Sandbakk et al., 2012b; 2013b). Hence, the fastest skier does not necessarily have the best technique. He/she may just be stronger or less fatigued. Further, while biomechanical cross-country skiing research has traditionally compared different levels of skiers (e.g. Bilodeau et al., 1996; Sandbakk et al., 2010; 2012b), technique analyses performed at an individual level would reduce the confounding factor of individual physiology and anatomical differences. However, longitudinal studies of technique development or technique training interventions are lacking in the cross-country skiing literature.

2.2.4 Technique quality and essential measurements

Ideally in sports, technique analysis should lead to improved technique and enhanced performance (Lees, 2002). In this thesis, *technique quality* refers to how well the technique is optimized. The *best optimized technique* is defined as the movement pattern that best adapts to the external conditions, by capitalizing on the skier's physiological potential and maximizing performance at an individual level.

To maintain a certain speed, the average propulsive force impulse from poles and skis must equal the braking force impulse due to gravity, air resistance, and snow/rolling friction. The temporal patterns of ground contact, which define the sub-technique, show when ground reaction forces are applied, but not the amount and direction of the forces. For any given sub-technique there is room for variation in movements, both within and between skiers (see section 2.2.3). Some modifications can also be generalized. For example, the "double push" technique has been shown to be faster than the normal V2 technique in short sprints (Stöggl et al., 2008; 2010). The visually different coordination of the double push compared to V2 movements includes the initial direction of the skis, and a distinct elevation of center-of-mass (jump) while re-directing the skis prior to the ski push (Stöggl et al., 2008). Coordination of movements ("timing") has also been suggested to differentiate faster and slower skiers (Stöggl et al., 2011). Examining such favorable "timing" requires detailed and continuous data to identify minor changes in essential movements. Including a large set of variables is preferable, and combining kinetic measurements with kinematic full-body analysis (e.g. used by Smith et al., 2009; Nilsson et al., 2013; Zoppirolli et al., 2015; Stöggl & Holmberg, 2015) is considered the best way to describe the technique. However, performing such analysis in the field is difficult, determining what changes are beneficial is not intuitive, and it is challenging to find a way of communicating the huge amount of information back to the athlete in a way that is easy to understand. Principal component analysis has recently been applied in sports (e.g. Federolf et al., 2014) and may be suitable for reducing the complexity of full-body analysis of cross-country skiing movements. Evaluating COM displacement is another alternative, as COM acceleration reflects the result of all forces acting on the athlete. COM analysis has also recently been more extensively used in cross-country skiing research (e.g. Smith et al., 2009; Sandbakk et al., 2013a; Pellegrini et al., 2014; Zoppirolli et al., 2015).

2.3 Inertial measurement units

Inertial sensors measure linear change in speed (acceleration), or angular rate, because of inertia. Both linear acceleration sensors (accelerometers) and angular rate sensing devices (gyroscopes) are inertial sensors and are often combined in a single *inertial measurement unit* (IMU). Inertial sensors measure not forces, but the result of forces. From the results obtained, speed and displacement can be calculated by time integration. This makes IMUs suitable for kinematic movement analysis, and their advantages include unlimited capture volume and reduced time costs (e.g. Krüger & Edelmann-Nusser, 2010).

The inclusion of IMUs in devices as smartphones has dramatically reduced the price and size of electronic IMUs. Today there is a large range of sensors with different specifications in terms of materials, measurement range, and sampling frequency. This results in sensors of differing quality, exhibiting a range of measurement errors (Titterton & Weston, 2004). Hence, specific systems must be validated for the intended use. For some purposes, using several types of sensors is crucial, but it also increases the complexity of algorithms, the price, and the number of potential sources of error. In some cases, multiple sensors may not be necessary to answer the research question—for example for automatic classification of sub-techniques in cross-country skiing (Stöggl et al., 2014).

When using IMUs it must be noted that the IMU measures the acceleration and angular rate of the segment it is attached to. Hence, the signal pattern will be affected by the IMU’s placement on the body. Since all forces and motion of body segments contribute to the final displacement of the COM, an ideal simple method for analyzing complex motion is to place the IMU precisely at the COM. However, the location of the COM depends on the configuration of the body segments, which changes constantly during dynamic movements like skiing.

Further, IMUs measure within a local coordinate system and while accelerometers are sensitive to gravity, gyroscopes are more sensitive to drifting errors. Gravity, drift, and misalignment between the IMU's local frame and the global coordinate frame are threats to the validity of the measurements. By incorporating gyroscopic data, differences between the local (IMU) and global reference frames can be corrected for. However, the sensor's initial position, speed, and orientation in the global coordinate system are unknown based on the inertial sensor's output alone. Hence, additional inputs are needed to strengthen external validity.

2.3.1 Use of constraints

One approach to finding the inertial sensor’s initial orientation is to include magnetometers measuring the direction of the earth's magnetic field. However, typical root-mean-squared (RMS) errors are up to 2° for heading orientations in controlled situations (Jiménez et al., 2009; Faber et al., 2013). In addition, magnetometers are also sensitive to other magnetic fields, including disturbances from metallic structures or power lines (Jiménez et al., 2009). Another approach to finding the initial position, speed, or orientation of the unit, and dealing with drift, is to include movement-specific constraints and some kind of calibration movement (e.g. Favre et al., 2009). For example, constraints have been used as follows:

- Horizontal acceleration is zero at constant speeds and gravity is always vertically oriented. Moe-Nilssen (1998a; 1998b) used these constraints and a tri-axial accelerometer mounted at the lower back to devise and validate an algorithm, which aligned the IMU's local reference frame to the global reference frame during walking.

- In ski jumping the slope and direction of the in-run can be measured. This constraint was used to calculate the IMU's orientation with respect to the global reference frame of a ski jumping hill (Chardonnens et al., 2014).

- The ski is stationary during the kick phase in the diagonal stride technique. To calculate speed and cycle length in diagonal treadmill roller-skiing, this constraint was used to reduce drift (Fasel et al., 2015).

2.3.2 Alternative names and additional sensors

Small IMUs are also called micro-electro-mechanical systems (MEMS) and the accuracy of MEMS had increased dramatically by 2004 (Titterton & Weston, 2004). When IMUs are combined with magnetometers the notation IMMU is sometimes used. Other sensors, such as barometric pressure sensors and temperature sensors may also be included in the units. Marsland et al. (2012; 2015) used a unit which also included a global navigational satellite system (GNSS). However, as this thesis focuses on the use of accelerometer and gyroscope data, the notation *IMU* or *inertial sensor* will be used even for more complex devices incorporating several types of sensors.

2.4 IMUs in sports

High sampling frequencies, small size, low price, low weight, easy preparation, unlimited space and time capture, and lack of interference with athletes' technique have favored the use of IMUs in the field of sport science. Inertial sensors were initially used for gait analysis (e.g. Moe-Nilssen, 1998b; Aminian et al., 2002; Kavanagh & Menz 2008), but the number of IMU-based papers in sport research is growing. In the last decade, IMU systems have been increasingly used for technique analysis in a range of team sports (Chambers et al., 2015), and in many individual sports including running (e.g. Lee et al., 2010), ski jumping (e.g. Chardonnens et al., 2014), and alpine skiing (e.g. Supej, 2010; Kruger & Edelmann-Nusser, 2010). A review by de Magalhaes et al. (2015) included 27 indexed articles or conference proceedings using IMUs in swimming, of which 21 were published after 2010. All studies included accelerometers and about a third of them used only a single accelerometer. About half of the studies did not include gyroscopes, and about one third included more than one sensor unit (de Magalhaes et al., 2015).

In cyclic movements such as walking, running and swimming, spatio-temporal variables including speed, cycle length, cycle frequency, and identification of phases have been calculated using IMUs. Additionally, Floor-Westerdijk et al. (2012) validated the use of a single IMU at the os sacrum (S1, lower back) for estimating COM displacement and reported RMS errors of < 8 mm during walking. However, limb movements and upper-body movements will affect accuracy and precision to some extent (Eames et al., 1999; Floor-Westerdijk et al., 2012).

In ski jumping, phase detection and timing, as well as hip, knee, shank, and ski angles have been calculated using IMUs (e.g. Chardonnens et al., 2013). Compared to traditional video methods, the system used by Chardonnens et al. (2013), consisting of seven IMUs, seems like a huge improvement. However, there are still further improvements to be made, particularly in terms of reducing errors in measurements of angles. For upper-limb joints, RMS errors up to 8° for isolated movements (El-Gohary & McNames, 2012) and 3° – 15° for simulated swimming have been reported (Fantozzi et al., 2016). For such angular measurements, two or more IMUs are synchronized. Suites including IMUs at "permanent" positions have also been used, for example in alpine skiing (Supej, 2010). However, while including several units will provide more detailed results for researchers, the systems may be too complicated for daily use by coaches and athletes.

2.5 IMU in cross-country skiing

Van den Bogert et al. (1999) were the first to use inertial sensors in research involving cross-country skiing. They used tri-axial accelerometers to estimate forces affecting accelerometers around the hip joint in different activities including cross-country skiing. However, they assessed whether activities were "safe" from a rehabilitation perspective, and did not analyze the movement patterns in detail (van den Bogert et al., 1999). Over the last five years, a growing number of studies using IMUs in cross-country skiing have been published (Table 2.5). Except for Fasel et al. (2015), who estimated spatio-temporal parameters in the classic diagonal style, the main topic has been sub-technique classification (n=7). Data from pole/wrist and ski/boot IMUs (Myklebust et al., 2011; Sakurai et al., 2014; 2016) seem to classify sub-techniques slightly better than pattern recognition from single-unit data, which correctly classify around 90% of all cycles (Stöggl et al., 2014; Marsland et al., 2015). Most miss-classifications are related to turns (Marsland et al., 2015; Sakurai et al., 2016) and technique transitions (Stöggl et al., 2014; Sakurai et al., 2016). The results are promising in terms of increasing the effectiveness of section-time analyses. In combination with a precise GNSS system, automatic sub-technique classification and transitions from IMUs would be much less demanding than using video recordings. Further, the summary in Table 2.5 shows that from one to and five IMUs have been used to examine classic (n=4) and skating (n=5) techniques, treadmill roller skiing (n=2), roller-skiing outdoors on asphalt (n=3), and on-snow skiing (n=3). The location of the IMUs in these studies varied between poles, upper chest, upper back, lower back, ski boots, and skis. Data from accelerometers and gyroscopes were used exclusively or in combination, and validations were mainly performed by video analysis. However, assessment of individual patterns and quantification of essential features were not performed.

Table 2.5 Published studies including IMUs in cross-country skiing (in chronological order). Papers published as part of this thesis are not included.

Reference	Sensor data used	Aim	Method	Findings
van den Bogert et al. (1996)	Four 3D accelerometers in a semi-rigid frame on the upper body. 300 Hz (EGAXT, Onset Computer Corporation, Bourne, MA).	To compare loading of the hip joint in alpine skiing, cross-country skiing, walking and running.	9 males tested in various activities, inverse dynamics.	Hip joint loading was higher for both classic and skating techniques compared to walking, but from a rehabilitation perspective, skiing was found safer than running.
Myklebust et al. (2011)	Accelerometer data from poles, ski boots and hip. 125-1000 Hz (PLUX Wireless Biosignals SA, Portugal).	Temporal pattern analysis and sub-technique classification while skating **on snow**.	3 elite skiers, 1.5 km sprint time trial. Video for validation.	Pole hits and leaves, and ski leaves were detected 99% correctly; ski hits were only 77% correct during stable technique; technique transitions were 88% correct. From hits and leaves, cycle time, poling time, pole reposition time, and asymmetry were successfully calculated, and individual differences illustrated.
Marsland et al. (2012)	3D accelerometer 3D gyroscope data from upper back. 100 Hz. (MinimaxX S4, Catapult Innovations, Australia).	Classic and skating sub-technique classification **on snow**.	8 skiers. Moderate speed. Flat and moderate uphill. Fixed sub-technique at each trial. Video for validation.	General patterns for all sub-techniques in both classic and skating were visually identified across all skiers.
Holst & Jonasson (2013)	3D accelerometer data from Android phones or Zephyr bio-harness mounted to the chest. 50 or 80 Hz	To develop and test an algorithm for skating sub-technique classification.	Statistical machine learning model and **asphalt roller-skiing** competition data.	100% classification on a training set of data from 7 skiers, and 98% classification on a test set of data from 7 different skiers.
Sakurai et al. (2014)	3D gyroscope data from wrists and skis. 100 Hz, GNSS position data at 5 Hz. (LP-WS0901, Logical Product Corp., Japan).	Classic sub-technique classification, examining relationships between speed, inclination and the sub-techniques used.	10 Japanese college skiers. 6.9 km time trial **roller skiing outdoors on asphalt**. Video for validation.	Out of 9444 cycles, 98.5% were automatically identified correctly. Some indications for sub-technique transition-threshold intensities were discussed, but no conclusions were presented.

Table 2.5 continues

Reference	Sensor data used	Aim	Method	Findings
Stöggl et al. (2014)	3D accelerometer data from a Sony Ericsson Xperia ST17i mounted to the front of the chest. 80 Hz.	Skating sub-technique classification using Smartphone accelerometer data.	11 regional to international level skiers. First machine learning. Then a 1.5 km time-trial course, **roller-skiing on a treadmil**l. Video for validation.	Accelerometer data from a Smartphone is sufficient for classification. For fixed techniques, classification was 100% correct. Machine learning on individual data increased correct classification from 86% to 90% of data including sub-technique transitions.
Fasel et al. (2015)	3D accelerometer 3D gyroscope at left pole and left roller ski. 500 Hz (Physiolog III, GaitUp, CH).	To automatically compute spatio-temporal parameters in diagonal stride.	10 jr to WC skiers **roller-skied on a treadmill** under 4 conditions. 3D infrared marker system for validation.	The system was sensitive enough to detect differences previously found for different terrains and fatigue. Accuracy and precision for cycle time and ski-push time were below 6 milliseconds, and below 35 milliseconds for poling time. Cycle speed and length precisions were < 0.1 m/s and < 0.15 m, respectively.
Marsland et al. (2015)	3D accelerometer 3D gyroscope data from the upper back. 100 Hz, GNSS at 10 Hz (MinimaxX S4, Catapult Innovations, Australia).	To validate classic sub-technique classification in terms of total time, cycle frequency, and cycle counts.	7 skiers at 2 sub-max intensities in a 0.5 km loop **on snow**. Video for validation.	78%, 74%, 88% correctly classified cycles in double poling, kick-double poling, and diagonal stride, respectively. Good reliability between IMU and video-calculated cycle frequency. Incorrect turn detection was a major factor in technique cycle misclassification.
Sakurai et al. (2016)	3D accelerometer 3D gyroscope data from wrists and skis. 100 Hz (LP-WS0901, Logical Product Corp., Japan).	Develop and validate automatic skating sub-technique classification	15 Japanese college skiers. 3.5 km time-trial **roller skiing outdoors on asphalt**. Video for validation.	Accuracy: 94.8% out of 6768 cycles automatically identified correctly. Precision: 87% – 98%. Most incorrect classifications related to turns (95%) and sub-technique transitions (5%).

2.6 Potential advantages of IMU analyses

2.6.1 Spatio-temporal kinematics

Ground-contact temporal variables have been included in studies comparing sub-techniques (e.g. Nilsson et al., 2004; Stöggl et al., 2008), external conditions (e.g. Millet et al., 1998b; 1998c; 1998d; Ohtonen et al., 2013), level of skiers (e.g. Sandbakk et al., 2012b), technique alterations with fatigue (e.g. Åsan Grasaas et al., 2014), and manipulation of cycle frequency (Millet et al., 1998a; Leirdal et al., 2013). When temporal variables are calculated from 2D video, the sensitivity of timing the events is limited by the traditional 25–50 Hz sampling frequency. Other methodological limitations are capture volume and time-consuming analysis. An alternative method with higher sampling frequency (≥ 100 Hz) uses the 3D kinematics of passive markers (e.g. Sandbakk et al., 2012a). However, this method has limited capture volume and is mainly restricted to the laboratory. Kinetic measurements—pole and ski forces—have also been used to extract ground-contact temporal kinematics (e.g. Millet et al., 1998a; Stöggl et al., 2008; Nilsson et al., 2013; Ohtonen et al., 2013; Åsan Grasaas et al., 2014; Stöggl & Holmberg, 2015). Using force plates underneath the snow allows skiers to use their own equipment (e.g. Vähäsöyrinki et al., 2008; Mikkola et al., 2013), but the method obviously has limited capture volume and the equipment is not commercial available. Instrumented poles and skis may be used in the field, but some modification of the skier's equipment is needed and some mass is added (e.g. Bortolan et al., 2009; Nilsson et al., 2013; Ohtonen et al., 2013), which may affect the skier's technique and excludes in-competition measurement.

A simpler system allowing spatio-temporal analysis in the field would be beneficial for skiers and coaches worldwide on a daily basis (Fasel et al., 2015). The sensitivity, accuracy, and precision of temporal patterns from IMU data show that IMUs are suitable for all purposes where temporal patterns have previously been reported (Myklebust et al., 2011; Fasel et al., 2015). This includes describing changes due to external conditions and fatigue, and differences between sub-techniques and skiers. As the system records continuously it will be possible to calculate inter-cycle variability (Fasel et al., 2015). Estimating speed and cycle length from IMU data is an interesting alternative, or addition, to speed calculated from GNSS (Fasel et al., 2015). However, Fasel et al. (2015) analyzed diagonal strides only, and the constraint used—static periods of the skis—is not valid while skating.

2.6.2 Assessment of technique quality

Measuring pole and ski forces is easier than estimating external forces. The relative contribution of arms and legs is also interesting as it differs between sub-techniques (Smith et al., 2009), and presumably between skiers. Force platforms have been used to quantify the relative amounts of propulsion (Nilsson et al., 2003; Vähäsöyrinki et al., 2008). Alternatively, force measurements must be combined with the kinematics of pole and ski angles (Smith, 2000). Only a few studies have combined force measurements with pole angles (Stöggl & Holmberg, 2011; Nilsson et al., 2013) and/or ski angles (Smith et al., 2009; Grasaas et al., 2014; Pellegrini et al., 2014; Zoppirolli et al., 2015; Stöggl & Holmberg, 2015). These studies all used passive markers and several high-speed cameras, and they were all restricted to a laboratory environment.

IMUs cannot measure the magnitudes of forces. The temporal pattern derived from IMUs on poles and skis can only show when the limbs *may* perform propulsion. However, as COM acceleration reflects the result of all forces acting on the skier, COM analysis can contribute to assessing the appropriateness of applied forces (Sandbakk et al., 2013a). COM displacement analysis is a simplified way to study kinematics, and is also useful without force measurements (e.g. Smith & Heagy, 1994). Sandbakk et al. (2013a) analyzed the effect of poling in comparison with non-poling when using V2 technique movements. They found vertical COM displacement to be greater and sideways displacement to be less with poling (Sandbakk et al., 2013a). Pellegrini et al. (2014) used COM displacement to calculate mechanical work in three classical sub-techniques. They stated that "*Improving the economy of skiing may thus depend on the ability of the skier to reduce the mechanical work related to execution of the technique, which is associated with the COM position and speed fluctuations*" (Pellegrini et al., 2014). The same research group has reported vertical COM displacement to relate to energy cost in double poling (Zoppirolli et al., 2015). COM can be estimated both from a setup including a suite of several IMUs (Supej, 2010), and from a single IMU at S1 (Floor-Westerdijk et al., 2012). However, this has not been tested while cross-country skiing yet and accuracy while skiing is probably reduced compared to walking because of the increased upper-body movement in skiing.

2.6.3 Non-focused potentials

Traditional methods of using either 2D video (e.g. Zory et al., 2009) or electronic goniometers (e.g. Perrey et al., 1998; Holmberg et al., 2005; Stöggl et al., 2008; Lindinger & Holmberg, 2011) for calculating joint angles have some drawbacks. As mentioned, video has a limited capture volume. 2D video is also sensitive to in-depth distance, resulting in considerable errors if segments are not in a plane perpendicular to the video camera. Electronic goniometers have unlimited capture volume, but the goniometers previously used are not suitable for measuring angles in the shoulder joint—a very important joint in cross-country skiing. IMUs can also potentially estimate joint and ski angles within certain limits of accuracy (see section 2.4). In addition, IMU data are numerical data, usually sampled at high frequency, without capture volume restrictions. If the sensors do not interfere with the skier's movements, IMU data are, in principle, well suited for immediate feedback. However, feedback, ski-, pole-, and joint-angles estimated from IMUs are not assessed in this thesis.

2.7 Aims of the thesis

The overall aim of this thesis was to assess how, and to what extent, IMUs can contribute to technique analysis in ski skating. The papers included in this thesis aimed to validate IMU-based methods, and to answer cross-country-skiing-specific research questions concerning the skating technique using IMUs. Specifically the aims were to:

- Evaluate reproducibility of hip movement pattern as measured by IMUs (Study I).
- Describe hip movement pattern measured by IMUs during V1 and V2 skating (Study I).
- Validate IMU-derived ski-skating hip and center-of-mass displacement, and ground-contact temporal patterns (Studies I-II).
- Assess the effect of technique alterations, measured by IMU data, on work economy and performance (Study III).
- Compare roller skiing and on-snow skiing in terms of movement patterns (Study IV).

The hypotheses were that:

H1 Movement patterns captured by IMUs differ systematically between sub-techniques (V1 and V2) and skiers, but are reproduced within skiers (Study I).

H2 Methods adjusting for intra-cycle hip rotations increase the accuracy and precision of estimating hip (S1) displacement from IMU data in both V1 and V2 (Study II).

H3 Errors between S1 and COM displacement are small, systematic, and negligible in both V1 and V2 (Study II).

H4 IMU data can quantify essential technique alterations affecting work economy and performance of elite skiers (Study III).

H5 There are only trivial differences between roller skiing and on-snow skiing techniques (Study IV).

3.0 Methods

3.1 Participants and ethics

In total 28 male skiers volunteered, with some skiers participating in several studies (Table 3.1). Studies I-III included national or international elite level senior male cross-country skiers, regularly tested on the treadmill over the past 1–4 years. All these skiers had top 30 rankings in Norwegian Championships, 14 skiers had participated in one or more International Ski Federation World Cup races prior to our studies, and three skiers in Study II were on the Norwegian national sprint team. Eleven of the skiers in Study I also participated in Study III. The nine well-trained skiers participating in Study IV were present or former active skiers. They all performed two familiarization sessions on the treadmill prior to the first test and were subjectively judged to have movement patterns with little variability. The studies were evaluated by the Regional Ethics Committee of Southern Norway, and the skiers gave their written consent before study participation.

Table 3.1. Skiers and intensity characteristics in Studies I-IV.

Study	**n**	**Age** (years)	**Height** (cm)	**Body-mass** (kg)	**VO$_{2peak}$** (mL·kg^{-1}·min^{-1})	**Level**	**Intensity**	**O$_2$ demand** (mL·kg^{-1}·min^{-1})
I	14	24 ± 3	182 ± 5	76 ± 8	76.2 ± 4.8	elite	4°, 3.0 m·s^{-1}	50.2 ± 2.4
II	6	26 ± 2	181 ± 5	80 ± 5	74.6 ± 5.2	elite	4°, 3.0 m·s^{-1}	48.1 ± 1.4
III	13	23 ± 2	182 ± 6	76 ± 8	79.3 ± 4.4	elite	6°, 3.5 m·s^{-1}	≈ 74–76 ≈ 97–100% of peak*
IV	9	24 ± 3	181 ± 3	81 ± 6	-	well-trained	8°, 3.0 m·s^{-1}	≈ 80*

Note. Data are mean ± SD; * estimated from Losnegard et al., 2012b; mL = milliliter; min = minute

3.2 Experimental approach

To examine how IMUs can contribute to ski skating technique analysis, a within-skier repeated-measures design was used (Studies I, III, IV). The skiers roller-skied on a treadmill (Studies I-IV), roller-skied outdoors on asphalt (Study IV), and skied on snow (Study IV). They used the V1 (Studies I-II) and the V2 (Studies I-IV) techniques, while temporal patterns of limb ground contacts and 3D hip movements (os sacrum, S1), were collected using an IMU system. In Study II, different numerical methods for estimating S1 and COM displacement from IMU data were validated against full-body 3D kinematics collected simultaneously. In Study IV, a within-skier crossover design was used to analyze the effect of friction on technique and performance. The two different pairs of skis (low and high friction) were tested in a controlled randomized order (Study IV).

All technique variables were analyzed using submaximal constant intensities (Studies I-II) or non-fatigued periods of constant intensity (Studies III-IV, Table 3.1). Additionally in Study III and Study IV, performance was measured as time in a 1000 m or 128 m time trial, respectively.

3.3 Equipment and data collection

3.3.1 Treadmill, skis and poles

All studies included roller skiing on a 3.0 x 4.5 m treadmill (Rodby, Södertalje, Sweden). Inclines and speeds were calibrated before, and checked during and after the testing periods. A pair of 67 cm-long Swenor Skate roller-skis (Swenor, Sarpsborg, Norway) with wheel type 1 (roller friction coefficient, $\mu \approx 0.018$), NNN binding system (Rottefella, Klokkarstua, Norway), and total mass of 870 grams per ski, was used in each study. A second pair with an SNS binding system was used in Study I and Study III, as some skiers used such bindings. In Studies I-III, the skiers used poles (CT1, Swix, Lillehammer, Norway) with customized tips, and self-selected pole lengths of 91% ± 1% of body height (manufacturer pole lengths).

In Study IV, two different pairs of skis (low and high friction) were tested in a controlled randomized order on all four test occasions. Outdoor tests—asphalt roller skiing in fall and snow skiing in winter—were performed on the same hill, and two to three skiers were tested each day. A metronome and marked lines on the ground were used to help the skiers monitor their speed and maintain it at 3.0 m/s over the 30 m-long data-collection area (Figure 3.1). During analysis the actual speeds were checked using video recordings. On snow, a test-series of eight Madshus Nanosonic Skate skis (Madshus, Biri, Norway) with a length of 190 cm and total mass (including binding) of 750 grams per ski, was used. Four pairs were well prepared while on the other four pairs the glide wax was not removed from the heel to 25 cm behind that point. All skiers used their own poles for outdoor roller-skiing and Swix Triac 1.0 poles were used on the remaining three test occasions. Pole tips were changed according to surface, but pole length was kept constant at 88% ± 1% of body height (pole tip to hand strap).

Figure 3.1. The 30 m-long outdoor data-collection area. To the left, photocells at fixed distances for calculating gliding friction.

3.3.2 IMU system

An IMU system from PLUX Wireless Biosignals S.A. was used in all studies. It consisted of three (Study II) or five (Studies I, III, IV) tri-axial accelerometers wired to a 12-bit data acquisition unit including battery and Bluetooth radio. Using medical tape, accelerometers were adhered to the poles and ski-boots (Studies I, III, and IV; Figure 3.2). These sensors collected single axis accelerations along the poles and orthogonal to the ski at heel-ski contact. The acquisition unit was attached next to the fifth (hip) accelerometer which was adhered directly to the skin at S1 in Studies I and III. In Study II and Study IV, one additional prototype unit including both accelerometers and gyroscopes was adhered at S1 with medical tape (Study II) or secured in a tightened waist belt (Study IV). In these two studies, the fifth PLUX accelerometer was adhered outside the Apertus unit (Figure 3.2). All IMU data were transmitted via Bluetooth radio for logging on a computer (MonitorPLUX 2.0, PLUX), or a custom-made smartphone application. Apertus data were logged at 101.2 Hz, PLUX data from S1 and ski boots at 1000 Hz, and pole data at 125 Hz (Studies I, III, and IV—because of acquisition unit limitations) or 1000 Hz (Study II). Total mass added to the skier was 140–550 grams including smartphones. Specifications of the IMUs are listed in table 3.2.

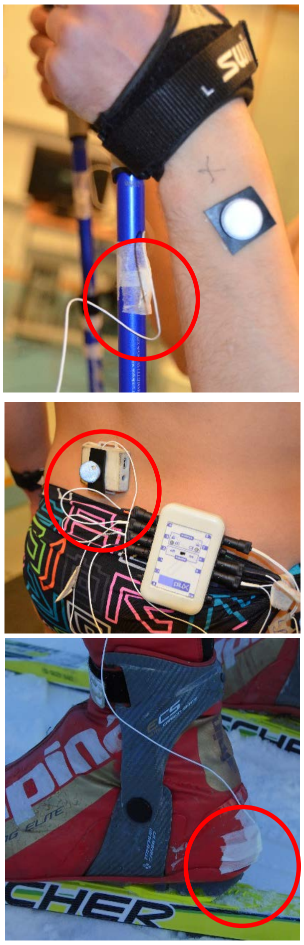

Figure 3.2. IMU locations.

Table 3.2 Extended details of inertial measurement unit (IMU) systems.

System	Manufacturer	Model	Dimension	Sampling rate	Range	Weight
IMU-A	PLUX Wireless Biosignals S.A., Lisbon, Portugal	researchPLUX, xyzPLUX accelerometers	10 mm × 20 mm × 5 mm	Up to 1000 Hz	± 3 g	85 grams data acquisition unit, 11 grams per accelerometer
IMU-G	Apertus AS, Asker, Norway	Prototype, 3D accelerometer, 3D gyroscope	55 mm × 38 mm × 10 mm	101.2 Hz	± 2 g 250 °/s	25 grams

Note. mm = millimeter; ° = degrees; g = gravity = 9.82 m·s^{-2}

3.3.3 Video capture

Two-dimensional video was captured simultaneously with IMU data collection for visualization in case unexpected artefacts occurred in the IMU signals. On the treadmill, video was captured from a distance of 6.6 m perpendicular to the skiing direction (Study I and Study III: Sony DCR-TRV900E; Sony, Tokyo, Japan). In Study IV, two identical Canon HF100 cameras (Canon, Tokyo, Japan) captured video laterally and from behind the skier, both on the treadmill and outdoors. Additionally in Study I, the video (50 Hz) was used for validation of the pole and ski plants and liftoffs, identified automatically by the IMU system. For synchronization of video and IMU data in this study, the video recorded a computer screen where a trigger, manually sent to the IMU, occurred.

3.3.4 Full body 3D kinematics

In Study II, forty-four reflective markers (dimeter = 20 mm) were mounted on body landmarks and equipment (Figure 3.3) to collect full body 3D kinematics. The markers were tracked over 40 seconds at 250 Hz using a nine-camera optical motion system (Oqus 400, Qualisys AB, Gothenburg, Sweden). The S1 reflective marker was placed at the PLUX accelerometer which again was placed at the Apertus sensor (Figure 3.3).

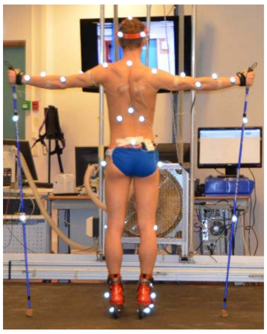

Figure 3.3. Reflective markers.

3.3.5 Oxygen cost

In Study III, submaximal oxygen cost (O_2-cost) was measured according to previous studies by our research group (e.g. Losnegard et al., 2012b). The individual O_2-cost (units: milliliter per minute) used for further analysis was calculated as the average of the three loads at 3.5°, 4.5° and 5.0°. These loads were completed by all skiers at all test time-points.

3.4 Analysis of IMU signals

As there is no specialized commercial software available for analyzing IMU data from cross-country skiing, our method was slightly modified between studies. All data were post-processed using Python 2.5.4 (Python Software Foundation, Beaverton, Oregon, USA) in Study I or Matlab R2012b (MathWorks Inc., Natick, MA, USA) in Study II–IV.

In all studies, a right-handed laboratory reference frame (XYZ) was defined to move along the surface with constant speed corresponding to the time average of the skier's COM, with the XY-plane horizontal, and the positive Y-axis pointing in the anterior direction. Calibration of the accelerometers was done according to Lai et al. (2004), using offset and scaling factors specific for each accelerometer. For gyroscope data (Studies II and IV), the manufacturer's default scaling factors were used, while offset values were calculated from a static measurement on the day of testing. All IMU data were filtered using a 30 Hz low-pass second order Butterworth recursive digital filter. The cut-off frequency was selected based on residual analysis of the signals.

3.4.1 Temporal patterns

The ground-contact temporal-pattern analysis used in all four studies was similar to the algorithm presented by Myklebust et al. (2011). It determines the time of ground contact for poles and skis, as visually illustrated in Figure 3.4. The plants and liftoffs are calculated based on algorithms combining jerk (first derivative of the acceleration signal), span (second derivative of acceleration signal), signal smoothing, thresholds, and skiing-specific constraints. Time points of plants and liftoffs in all trials were visually inspected. Thresholds and use of constraints to restrict the time window where plants and liftoffs could occur, sometimes needed adjustment between studies, conditions (snow vs. treadmill), and skiers (Figure 3.4).

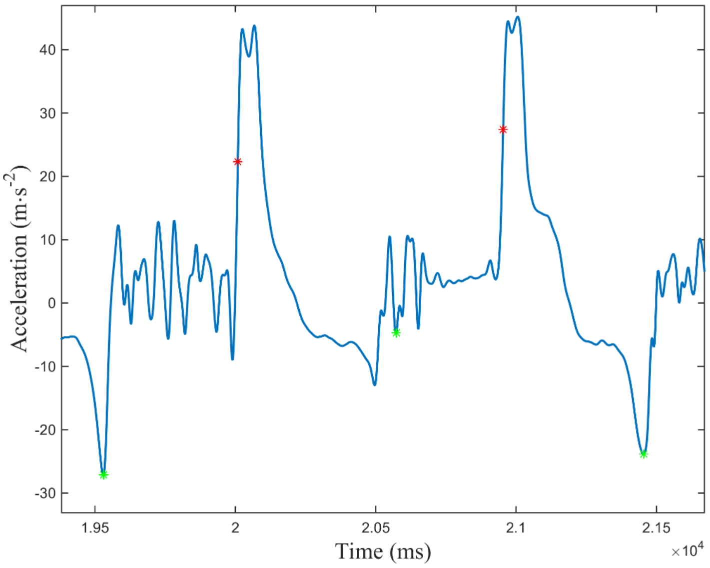

Figure 3.4. Pole acceleration signal for one V2 cycle. Green and red dots indicate plant and liftoff, respectively. Visually incorrect pole plants, as illustrated by the middle pole plant, occurred in about 1% of all pole plants, and were adjusted.

In study I, ski liftoffs were used to separate cycles, and the temporal patterns of full cycles for both sub-techniques used are illustrated in Figure 2.1. For Studies II–IV a full cycle is illustrated in Figure 2.3. Cycle time was defined as the time for a full cycle. Poling and gliding time were defined as time with ground contact of poles and skis, respectively (illustrated by bars in figures), while reposition time was defined as time without ground contact. In V2, kick-phase time and pure glide time were defined, respectively, as time for the ski push without pole ground contact and time for ground contact by one ski only (Studies III–IV).

3.4.2 Hip movements

The method differed somewhat between studies. Study IV includes our current method and is therefore presented first.

Study IV: The algorithm followed these chronologically ordered steps:

1. A calibration motion (in which the skier performed five hip flexions/extensions) and a rotation matrix procedure (minimizing movements except for rotation around the X-axis), were used to fulfil the assumption that the S1 sensor's local coordinate frame was aligned with the laboratory frame when the skier stood in an anatomical neutral position. Flexion/extension was assumed to occur around the X-axis only.
2. Three dimensional data (Study II only) and IMU data from the PLUX and Apertus systems (Study II and Study IV), were time-synchronized using unbiased cross-correlation (Moe-Nilssen & Helbostad, 2004), before all signals were resampled to 100 Hz.
3. The effects of intra-cycle rotations were corrected for using angular rates measured by the gyroscopes and the strapdown inertial navigation algorithm described by Titterton & Weston (2004). To reduce drift in the orientation estimates due to offset errors in gyroscope output, the linear trend-line over the analyzed time period was subtracted from the Euler angles.
4. The inclinometer properties of accelerometers and a rotation matrix—first cancelling forward tilt angle, then lateral tilt angle (Moe-Nilssen, 1998a)—were applied to meet the constraint that average horizontal acceleration is zero at constant speeds.
5. Gravity (1.0 g) was subtracted from vertical acceleration signals to ensure average acceleration over the collection period was zero in all directions.
6. Data were time-normalized to a full cycle, using cut-points automatically derived from pole accelerometers.

7. A cumulative trapezoidal numerical integration was applied twice, and the corresponding cycle's average was subtracted for each integration step, to obtain the displacement of S1 in each cycle.
8. An average over a total of 15 cycles (3 trials including 5 consecutive cycles) was used for each skier's average curve.

Study I: The method included a tri-axial accelerometer only, and was identical to the IMU-A method validated in Study II. However, in Study I an average over 6 consecutive cycles was used for each individual skier's curve. For further details, see the paper from Study I.

Study II: Two different methods were validated. Apart from excluding the flexion/extension calibration motion in step 1 above, the IMU-G method was identical to the algorithm used in Study IV. For details of the validated IMU-A method, see the paper from Study I. An average over 15 consecutive cycles was used for individual skier's curves.

Study III: Gyroscopes were not included in this study. Instead, the method adjusted for intra-cycle rotations by performing step 4, step 6, a rotation matrix in combination with the V2-specific hip rotation pattern determined experimentally in Study II (Figure 4.2.1), step 5, step 7, and step 8 using ten consecutive cycles.

3.4.3 Reference values

In Study II, COM was calculated based on a 19 body-segment model. The model was derived from Visual 3D models (C-Motion Inc., Germantown, MD, USA), measurements of the equipment, and the anthropometrics of the skier. The time average of each cycle was subtracted from the S1 and COM data after dividing signals into cycles. Hence, reference values for S1 and COM displacement were obtained for comparison with the IMU estimates.

3.5 Statistics

All data are presented as mean ± standard deviation (SD) if not otherwise stated. Two-sided paired t-tests were used for comparison of sub-techniques (Study I), synchrony of pole thrusts on right and left sides in V2 (Study I), and technique in June compared to January (Study III). In Study I and Study IV, a repeated measures ANOVA using Bonferroni correction was used to check for statistically significant differences between different test time-points. The magnitude of the differences was expressed as standardized mean differences (Cohen’s *d* effect size; ES). Thresholds for interpreting differences as small, moderate, large and very large ES were 0.2, 0.6, 1.2, and 2.0, respectively (Hopkins et al., 2009).

For validity of ground-contact temporal kinematics (Study I) and S1 displacement (Study II), the group mean difference represents the IMU-method's accuracy and the SD represents the precision of a single estimation. In Study I and Study IV, within-subject typical variation (named "typical error" in study I) and Pearson's product moment correlation coefficient are presented for reproducibility of the hip acceleration parameters between trials. Pearson's correlation coefficient was also calculated in Study III, both for log-transformed raw data and for log-transformed change scores from June to January. Thresholds for large, very large and extremely large correlation coefficients were 0.5, 0.7, and 0.9, respectively (Hopkins et al., 2009).

In Study II, validity was evaluated along each of the three orthogonal laboratory axes. RMS error quantified overall deviation between estimated (IMU data) and reference values (3D marker data) for a full cycle. Range-of-displacement (maximum-minimum amplitude) and timing-of-peak-amplitude (relative timing) deviations quantified whether the differences were caused mainly by amplitude or timing errors, respectively.

Statistical calculations were performed using Microsoft Excel (Redmond, WA), SigmaPlot (Systat Software Inc., San Jose, CA), and SPSS (IBM Corp., Armonk, NY). A *P*-value < 0.05 was considered statistically significant, and *P* < 0.10 was considered a tendency.

3.5.1 Linear mixed model

In Study III, a linear mixed model was used to evaluate the effect of technique alterations on performance. The strength of such a model is that it allows for repeated measurements and individual responses, while it is not very sensitive for missing data. Since the performance was measured as an uphill time trial it is obvious that altering weight will influence the amount of external work to be performed and hence the performance. It is also natural that the skiers (as a group) will improve as the season progress and the main events approach (e.g. because of physiological effects of adjusted training loads etc.). Figure 3.5 illustrates how a relationship between a technical variable and performance can be an artifact because both variables vary over time, and how removing the time-point effect can make causal relationships clearer. The model used adjusted for change in body mass and test time-points as fixed effects. Log-transformed change scores from each individual's average of available tests were used to ensure uniformity and retrieve relative changes. Since O_2-cost was found to be a strong mediator for the technical variables' effect on performance, O_2-cost was used as the dependent variable. Technical parameters were included in the model one by one, because of the limited amount of data (50 tests).

Relative change slopes (% per %) with ± 90% confidence limits, within-skier variation over the whole season, and residuals of models for each variable were determined. Technical variables were considered important if they reduced the effect of test time-points and/or reduced the model residual. Using magnitude thresholds presented by Hopkins et al. (2009), the smallest worthwhile effect of 1.1–1.4 % of ski racing times found by Spencer et al. (2014), and adjusting for O_2-cost's effect on performance resulted in magnitude thresholds of 0.5%, 1.6%, 2.8%, and 4.3% of O_2-cost, for small, moderate, large and very large performance effects. The following scale was used for probabilistic terms describing positive, negative or trivial effects: < 0.5%, most unlikely; 0.5%–5%, very unlikely; 5%–25%, unlikely; 25%–75%, possibly; 75%–95%, likely; 95%–99.5%, very likely; > 99.5%, most likely (Hopkins et al., 2009).

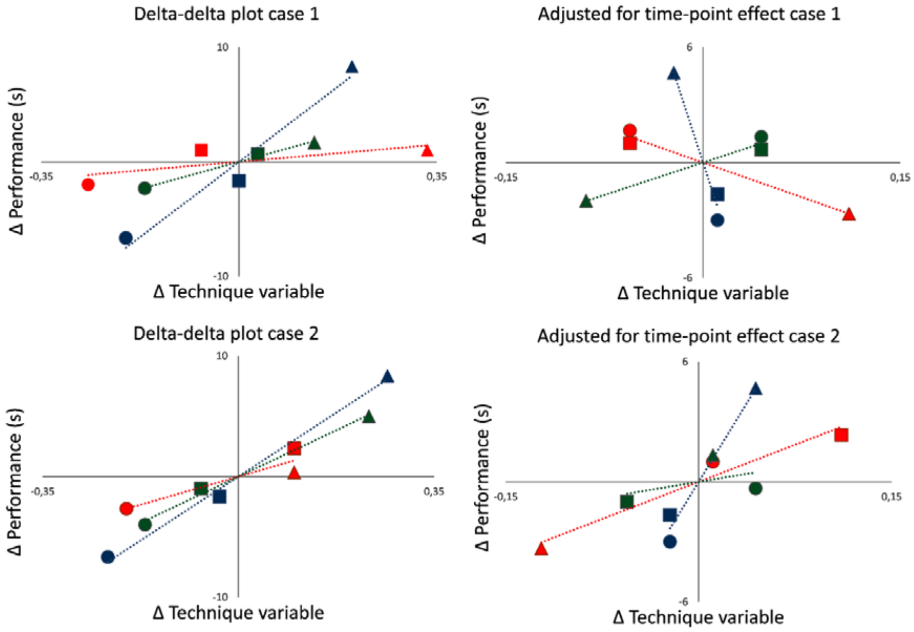

Figure 3.5. Individual relationships between change in a technical variable and performance. Different colors and symbols represent different skiers and test time-points, respectively. Clustered symbols on the left figures indicate time-point effects. The figures to the right show the relationships when the time-point effect, estimated as the average for the group, is subtracted from both the technical variable and performance. Hence, only the lower example indicates a causal relationship, where reducing the technical variable will also reduce performance time. Note that the values used are for illustration of the principles involved and do not represent actual measurements.

4.0 Results

For each of the four studies included in this thesis, a short summary of the design, hypotheses, methods, and results will follow. Note that some additional results, not included in the papers, are presented here.

4.1 Study I – Differences in V1 and V2 ski skating techniques described by accelerometers

A combination of cross-sectional, crossover, and longitudinal designs were used to test the hypothesis: "Movement patterns captured by IMUs differ systematically between sub-techniques (V1 and V2) and skiers, but are reproduced within skiers". Three-axial hip accelerations of fourteen elite skiers were collected during treadmill roller-skiing on a fixed inclination and speed (4° and 3 $m \cdot s^{-1}$). Uniaxial limb accelerometers detected ski- and pole-plants and liftoffs used for calculating ground-contact temporal patterns. Data from three time points were analyzed; twice from the same day in June (T1 and T2, separated by 20 minutes) and once in October (T3). At T1 the skiers performed both V1 and V2 techniques to evaluate the difference between the techniques. At T2 and T3 only V2 skiing data were collected, to test the reproducibility of the movement patterns. Plants and liftoffs from T1 were validated against 50 Hz video recordings.

The main findings were:

- Elite skiers showed individual hip movement patterns, which the skiers reproduced within and between tests (Figure 4.1.1). For instance, sideways range of displacement in V2 showed a variation between skiers of 38% (2xSD), while the test-retest correlation (Pearson's r) was 0.82. Test-retest correlations > 0.8 were also found for vertical and antero-posterior maximum and minimum acceleration, and antero-posterior range of displacement.

- Poling frequency (0.72 ± 0.04 Hz vs. 1.04 ± 0.07 Hz), timing of poling within the cycle, and well-defined hip movement patterns differed between the V1 and the V2 techniques (Figure 4.1.2). The V2, but not the V1, showed similarities to double poling in the way that the hip was lowered during the poling, and elevated between pole thrusts (Figure 4.1.2).

- Except for ski plants, accuracies better than the sensitivity of the video reference system were found for limb plants and liftoffs (Table 4.1).

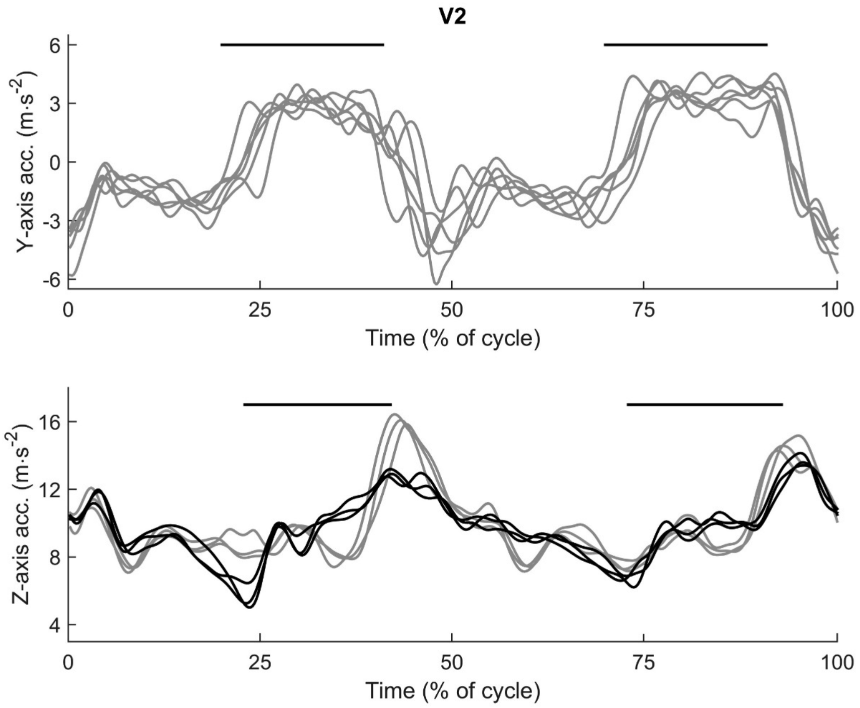

Figure 4.1.1. Time-normalized acceleration (acc.) in V2 cycles starting (0%) and ending (100%) with right ski liftoff. Horizontal bars indicate pole thrusts. Upper: Within-run reproducibility presented as six consecutive cycles in the antero-posterior (Y-axis) direction. Lower: Between-skier comparison (black vs gray) of vertical (Z-axis) acceleration for three runs (time points: 0, +20 minutes, and + 4 months). Each curve represents the mean of six consecutive cycles.

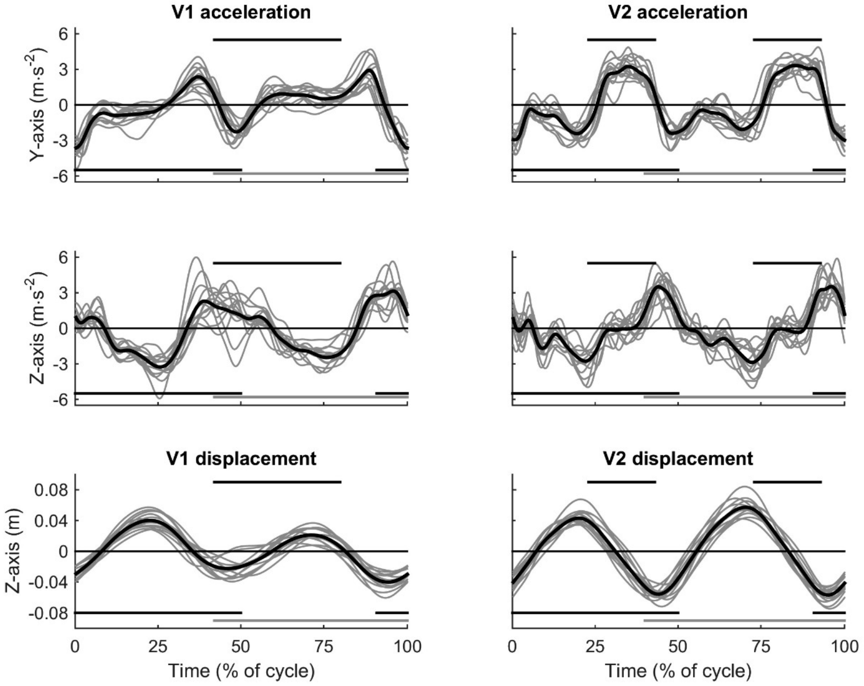

Figure 4.1.2. Antero-posterior (Y-axis) and vertical (Z-axis) hip (S1) acceleration curves and vertical displacement curves (the bottom plots) time-normalized to a full cycle for V1 (left) and V2 (right). Each line represents one subject. The black line is the group mean curve. Black horizontal bars in the upper part of each panel indicate timing of poling. Black and gray bars in the lower part of each panel indicate left and right ski ground contact, respectively. Hence, right ski liftoff starts and ends the cycle.

Table 4.1. Estimated timing of plants and liftoffs from IMU data compared to 50 Hz video analysis. Positive differences mean that the video detected the event before the algorithm.

	N	**Pole plant**	**Pole liftoff**	**Ski plant**	**Ski liftoff**
V1 (ms)	84 or 168	9 ± 34	-13 ± 27	39 ± 56	6 ± 31
V2 (ms)	144	6 ± 37	-12 ± 25	47 ± 74	-1 ± 23

Note. Values are mean ± SD in milliseconds (ms); Data from 6 subjects, 2 trials per subject in each technique, 6 ± 1 cycles per trial. Only the right pole was analyzed.

4.2 Study II – Validity of Ski Skating Center-of-Mass Displacement Measured by a Single Inertial Measurement Unit

This validation study addressed the questions: 1) How accurately can a single IMU estimate hip displacements during ski skating in elite skiers? 2) Does incorporating gyroscope and accelerometer data increase the accuracy and precision of estimation of hip movements compared to accelerometer data alone? 3) How accurately does os sacrum (S1) displacement estimate COM displacement? The two hypotheses were: "Methods adjusting for intra-cycle hip rotations increase the accuracy and precision of estimating hip displacement from IMU data in both V1 and V2", and "Errors between S1 and COM displacement are small, systematic, and negligible in both V1 and V2."

Two different IMU systems were attached and placed posterior to S1 to collect hip movement data. One system included a three-axial accelerometer only (IMU-A, identical to the one used in Study I), while the other system included both a three-axial accelerometer and a three-axial gyroscope (IMU-G). Additionally, right pole plants and liftoffs were detected by a uniaxial accelerometer placed at the pole. IMU data and 3D full-body optical kinematics were collected while six elite skiers roller-skied on a treadmill (4° inclination and 3 $m \cdot s^{-1}$) using both the V1 and the V2 techniques. The reflective marker at S1, and COM calculated from a 3D full-body optical kinematic analysis, were used to provide reference values.

Findings:

With accelerometer data only (IMU-A), vertical (Z-axis) S1 displacement was estimated relatively accurately, as evidenced by an RMS error of 10 (2) mm in V2. In the two other directions, the error was larger, mainly because of a time-shift in the sideways direction, and both a time-shift and an amplitude difference in the antero-posterior direction. Correcting for intra-cycle rotations using the gyroscope data (IMU-G) reduced both time-shift and amplitude errors. Hence, IMU-G increased accuracy and precision in all directions (Table 4.2). The IMU-G method achieved an accuracy of < 8 mm, for both RMS error and range-of-displacement deviation, in all directions for both sub-techniques (Table 4.2). The RMS error of IMU-G in the antero-posterior (Y) direction was < 7 % of the S1 range of displacement, while the error in sideways (X) and vertical (Z) directions was < 2 % of the S1 range of displacement.

In Table 4.2 the IMU-A2 method is also included. This is the method used in Study III, which did not include gyroscope data. Instead it used the systematic hip rotation pattern (Figure 4.2.1) to correct for intra-cycle rotations. This reduced time-shifts in the signals and increased accuracy in all directions (Table 4.2).

Table 4.2. Differences between IMU methods and the reflexive marker at os sacrum (S1) in the laboratory reference frame.

Technique & Method		ROD Deviation (mm)			TPA Deviation (% of cycle)			RMS Error (mm)		
		X	Y	Z	X	Y	Z	X	Y	Z
V1	IMU-A	12 ± 31	-19 ± 23	6 ± 9	-5 ± 1	-5 ± 3	-1 ± 0	32 ± 7	24 ± 8	6 ± 1
	IMU-A2	-17 ± 27	2 ± 25	2 ± 3	0 ± 1	-1 ± 2	0 ± 0	11 ± 5	11 ± 6	2 ± 1
	IMU-G	1 ± 10	-1 ± 5	-1 ± 1	0 ± 1	1 ± 4	0 ± 0	4 ± 2	7 ± 6	1 ± 1
V2	IMU-A	3 ± 51	-36 ± 15	1 ± 5	-13 ± 6	0 ± 6	-2 ± 1	69 ± 14	23 ± 7	10 ± 2
	IMU-A2	-3 ± 46	2 ± 16	2 ± 6	0 ± 1	1 ± 3	0 ± 0	17 ± 9	13 ± 5	3 ± 2
	IMU-G	-6 ± 13	-7 ± 5	1 ± 1	0 ± 0	3 ± 2	0 ± 0	5 ± 3	7 ± 2	1 ± 0

Note. Group mean ± SD in millimeters (mm) or percent (%). IMU-A = Study I method including accelerometers only; IMU-A2 = Study III method including accelerometers only and the mean rotational pattern found in Study II; IMU-G = method used in Study II and Study IV combining accelerometer and gyroscope data; ROD = range of displacement; TPA = timing of peak amplitude; RMS = root-mean-squared; X = sideways; Y = antero-posterior; Z = vertical direction.

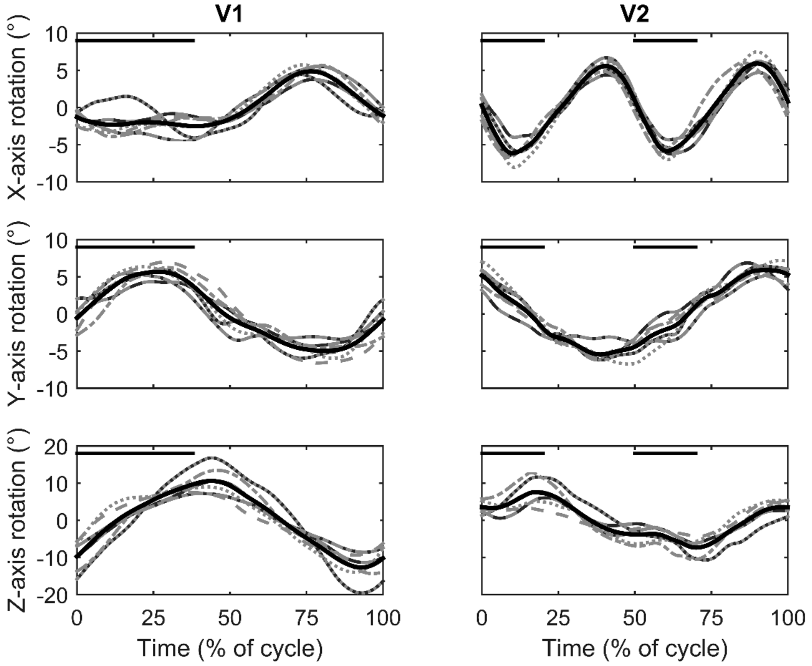

Figure 4.2.1 Individual hip rotation angles during a normalized cycle of V1 (left) and V2 (right). Positive X, Y, and Z angles indicate pelvis to be backward tilted, laterally tilted to the right, and heading to the left, respectively. Angles are calculated from pelvis markers. The black curves are the group average. Horizontal lines indicate pole thrusts. N = 6.

S1 displacement estimated sideways (X) COM displacement reasonably accurately (RMS error ~5%) for both V1 and V2 (Figure 4.2.2). In the antero-posterior (Y) direction, S1 overestimated the COM range of displacement by more than 100 %, and the RMS error was up to 72% of COM range of displacement. In vertical (Z) direction, S1 underestimated COM range of displacement by ~25% and the RMS error was ~18% of COM range of displacement. The amplitude and timing differences were systematic and caused by upper-body movements.

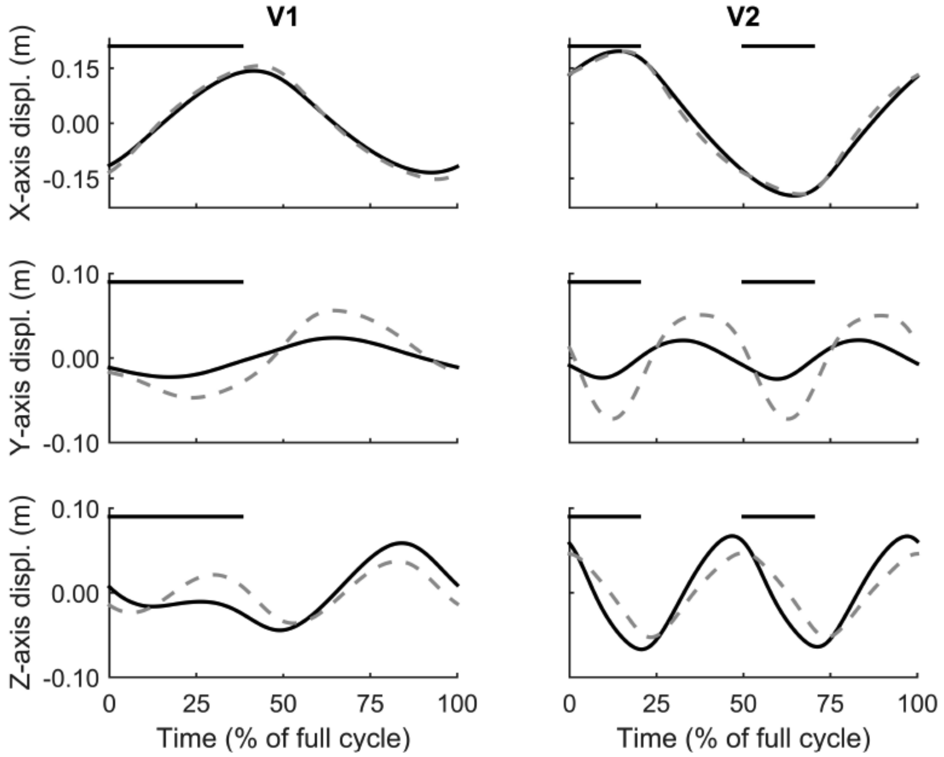

Figure 4.2.2 Time-normalized S1 (dashed line) and center-of-mass (black line) displacement (displ.) curves for V1 (left) and V2 (right) techniques in sideways (X), antero-posterior (Y) and vertical (Z) directions. Horizontal lines indicate pole thrusts. N = 6.

4.3 Study III: Kinematical analysis of the V2 ski skating technique: a longitudinal study

A longitudinal approach was used to test the hypothesis: "IMU data can quantify essential technique alterations affecting work economy and performance of elite skiers." Thirteen skiers were tested several times during a year of training. Their submaximal O_2-cost and 1000 m time-trial performances were measured. The time trials started at a fixed speed and during this section 3D hip accelerometer data were collected. Additionally, ground-contact temporal patterns were calculated from uniaxial limb accelerometers, as described in Study I. At two time points, data from eleven of the skiers were identical to the data in Study I. However, the IMU-A2 method validated in Study II was used to analyze hip accelerations in the present study.

Mixed modelling allows for repeated measurements with missing data (two to five tests) and individual responses. Hence, a mixed model was used to evaluate the effect of technique alterations on performance. As O_2-cost was found to be a strong mediator for technical variables' effect on performance, O_2-cost was used as dependent variable. The model adjusted for changes in body mass and time-point effects, for example, because of the physiological effects of adjusted training loads within the season). Technical parameters were included in the model one by one. Within-skier variation over the whole season, relative changes in slope (% per %), and model residuals are presented. A reduced effect of test time-point and/or reduced model residual was expected for important technical variables. Results were evaluated using magnitude-based inference.

The main findings from the IMU data were that:

- All skiers displayed reduced O_2-cost as the season progressed, but both cycle time and smoothness of hip movements (RMS vertical acceleration) modified the effect of time points, showing a small likely effect on performance (Figure 4.3, Table 4.3).

- Right ski thrust was automatically divided into three visually distinct phases: (I) Gliding phase (18–50% of cycle time); (II) poling phase (50–70% of cycle time); and (III) kick phase (70–78% of cycle time). Phase I overlaps with the left ski kick phase. Thus, a pure glide phase (Right ski as the only ground contact) was distinct from ~28% to 50% of cycle time.

- Alterations in cycle time were related to both the poling (phase II) and the pure glide phase, but not the kick phase (phase III). Video data revealed that the altered poling time (phase II) was related to pole-tip position at pole plant.

- Vertical hip acceleration in the middle of the pure glide phase (i.e. at 38–45% and 88–95% of cycle time; "middle pure glide") affected O_2-cost and performance to the same extent as full cycle vertical hip acceleration (Table 4.3). This indicates that it is important to improve balance even in elite skiers.

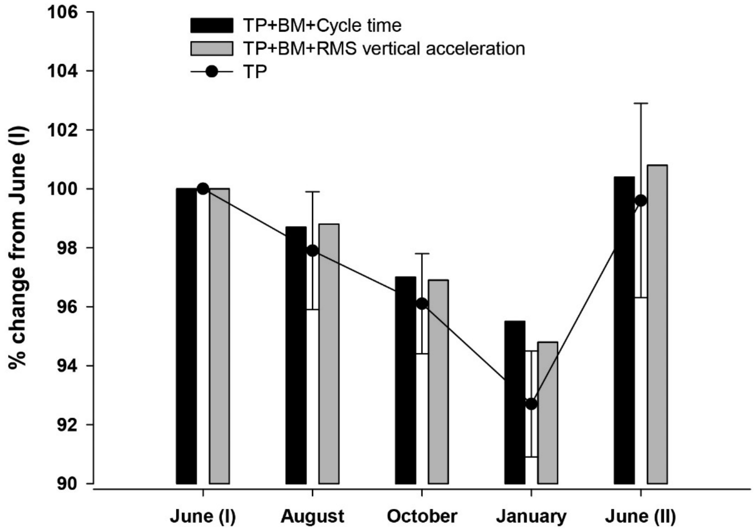

Figure 4.3. O_2-cost at different test time-points (TP; black line; mean ± 90% confidence limits) and how models adjusting for total mass (BM; body mass including equipment mass) and technical variables (cycle time or RMS vertical acceleration) modify the time-point effect. Note that only two skiers were analyzed in June (II).

Table 4.3. Effect of altered technical variables on O_2-cost (Slope) and performance (Effect size) derived from a mixed model allowing for individual responses, and adjusting for fixed effects of test time-point and changes in total mass.

	CV (%)	**Slope % per %**	**Effect size**				**Residual (%)**
Test time-point							5.2
Total mass	1.2	0.92 ± 0.49	2.21	±	1.18	Moderate	3.9
Cycle time	**4.3**	**-0.18 ± 0.17**	**-1.50**	**±**	**1.40**	**Small**	**3.5**
Poling time	**5.0**	**-0.16 ± 0.15**	**-1.52**	**±**	**1.28**	**Small**	**3.4**
Pole reposition time	**4.3**	**-0.13 ± 0.17**	**-1.08**	**±**	**1.41**	**Small**	**3.7**
Kick-phase time	6.2		-0.13	±	1.08	Unclear	4.0
Pure glide time	**5.9**	**-0.09 ± 0.12**	**-1.08**	**±**	**1.43**	**Small**	**3.7**
RMS acc sideways	4.0	0.06 ± 0.17	0.47	±	1.32	Unclear	3.9
RMS acc antero-posterior	7.3		-0.01	±	1.26	Unclear	4.0
RMS acc vertical	**6.7**	**0.10 ± 0.11**	**1.30**	**±**	**1.36**	**Small**	**3.6**
RMS acc resultant	5.3	0.09 ± 0.14	0.90	±	1.45	Unclear	3.8
RMS acc vertical, pure glide	10.0	0.05 ± 0.07	0.98	±	1.26	Possibly, small	3.7
RMS acc vertical, middle pure glide	**21.5**	**0.03 ± 0.04**	**1.36**	**±**	**1.48**	**Small**	**3.6**
RMS acc vertical, poling	7.9	0.04 ± 0.08	0.61	±	1.18	Unclear	3.9
RMS acc vertical, kick phase	7.2	0.06 ± 0.08	0.85	±	1.12	Possibly, small	3.8

Note: Data are mean ± 90% confidence limits. RMS acc = root-mean-squared acceleration. Total mass is body mass including equipment. CV is within-skier variation over the whole season. Magnitude of effect size is 2·CV·Slope, calculated according to Hopkins et al. (2009) and Spencer et al. (2014). Probability of effect size is "75%–95%, likely" if no other probabilistic term is noted. One technical variable was included at a time.

4.4 Study IV: Kinematic differences between treadmill, asphalt, and on-snow ski skating

A repeated measures design was used to test the hypothesis: "There are only trivial differences between roller skiing and on-snow skiing techniques." IMU data from nine well-trained skiers were collected during several short trials (< 40 seconds) at constant intensity ($3.0\ \mathrm{m \cdot s^{-1}}$, 8.0°, $\mu \approx 0.03$). Except for an additional calibration movement, the hip IMU data were collected and analyzed according to the IMU-G method validated in Study II, using both accelerometer and gyroscope data. Ground-contact temporal patterns were calculated from uniaxial limb accelerometers as described in Study I. Treadmill roller skiing was performed in both fall and winter. Outdoor tests were performed on the same uphill course for roller-skiing on asphalt (Fall) and on-snow skiing (Winter). The V2 technique was analyzed and two different pairs of skis (low and high friction) were tested in a controlled-randomized order at all occasions. The outputs were hip accelerations, rotations, and displacements, as well as ground-contact temporal patterns.

The main findings were:

- No significant differences between treadmill and asphalt roller skiing were found.

- Ground-contact temporal patterns of roller skiing and on-snow skiing showed large to very large Pearson correlation coefficients ($r = 0.68 – 0.84$, $P < 0.05$).

- Compared to treadmill roller skiing, a small increase in cycle time was found for both on-snow skiing and low-friction roller skiing. For on-snow skiing the increase was because of a moderately longer poling time, while for low-friction roller skiing it was because of a small increase in pure glide time (Table 4.4).

- On-snow skiing was characterized by an altered hip rotation pattern (Figure 4.4), greater lateral hip displacement, and a tendency to smoother hip movements (less accelerations) compared to roller skiing (Table 4.4). Rolling/gliding friction could not explain the differences between on-snow and roller skiing, since similar frictions were compared.

- Reducing the friction by 38% revealed smoother hip movements and a moderately shorter vertical range of displacement compared to high-friction roller-skis. The rotational patterns were not significantly altered by reduced friction (Table 4.4).

Table 4.4. Time of cycle phases, pelvis range of displacement (ROD), pelvis range of motion (ROM) and root-mean-squared acceleration (RMS acc.) along/around the sideways (X), antero-posterior (Y), and vertical (Z) axis.

		SD_w	Winter (n=9)				
	Surface		Snow		Treadmill		Treadmill Low friction
	Friction		0.028 ± 0.002		0.029		0.018
Time (ms)	CT	43	1773 ± 135	$^{\#S}$	1704 ± 98	^{*F}	1753 ± 124
	PT	15	422 ± 41	^{*S}	386 ± 31		391 ± 32
	Kick phase	6	83 ± 32		94 ± 21		97 ± 20
	Pure glide	15	381 ± 46		359 ± 27	^{*F}	377 ± 34
	RT	17	467 ± 53		465 ± 41	^{*F}	483 ± 46
ROD (cm)	X	2.6	44.1 ± 7.1	^{*S}	37.2 ± 6.6		38.6 ± 6.5
	Y	1.3	13.1 ± 2.6		14.5 ± 2.4		13.9 ± 2.4
	Z	0.6	17.3 ± 1.9		17.1 ± 2.3	^{*F}	15.7 ± 2.1
ROM (°)	X	1.7	14.4 ± 4.9		16.6 ± 5.9		15.9 ± 5.4
	Y	0.8	14.5 ± 2.1		14.1 ± 2.8	$^{\#F}$	13.1 ± 3.0
	Z	3.3	22.2 ± 7.7	^{*S}	14.1 ± 4.7		15.0 ± 5.2
RMS acc. (Nm·s^{-2})	Resultant	0.1	5.7 ± 0.4	$^{\#S}$	6.2 ± 0.4	^{*F}	5.7 ± 0.4
	X	0.1	3.0 ± 0.3		3.1 ± 0.3		3.0 ± 0.4
	Y	0.1	3.2 ± 0.3	^{*S}	3.5 ± 0.2	^{*F}	3.3 ± 0.2
	Z	0.2	3.2 ± 0.4		3.5 ± 0.3	^{*F}	3.1 ± 0.3

Note: group mean ± SD; CT = cycle time; PT = poling time; Kick phase = time between right pole and right ski liftoffs; Pure glide = gliding time on right ski only; RT = pole reposition time; ms = milliseconds; cm = centimeters; ° = degrees; * $P < 0.05$; # $P < 0.1$; ^{S} different from Snow; ^{F} different from low friction; SD_w within skier typical variation based on the two treadmill tests (Fall and Winter).

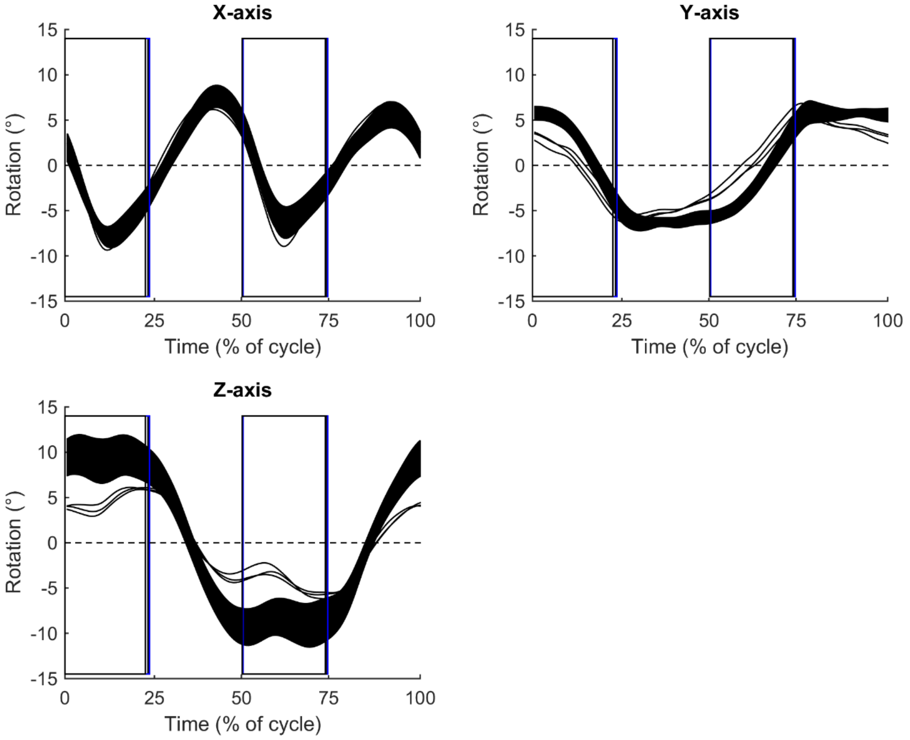

Figure 4.4. Time-normalized group-averaged rotation patterns for the three roller-ski tests (black lines), and 90% confidence limits for the on-snow skiing test (filled area). Positive X, Y, and Z-angles indicate the pelvis to be backward tilted, laterally tilted to the right, and heading to the left, respectively, compared to the average orientation of the pelvis within the cycle. Magnitudes of confidence limits were similar for all tests. Vertical lines indicate pole thrusts. N=9.

5.0 Discussion

Over the past five years, four other research groups have published, in total, seven papers involving the use of IMUs in cross-country skiing studies (Table 2.5). The focus of these papers has mainly been sub-technique classification, using different pattern recognition algorithms. The present thesis aims at assessing to what extent IMU data can also quantify essential movement features within a specific sub-technique. For this purpose, between-skier differences, external condition differences, and changes in technique in individual skiers were assessed in terms of temporal patterns of limb ground-contact and hip acceleration, speed, displacement, and rotation. Two of the present papers have a methodological focus on internal and external validity, and two papers are more applicable to skiers and coaches. The main conclusion is that IMUs are useful tools for quantifying essential movement features during both roller-ski and on-snow ski skating. The results include these new findings:

- Detailed description of temporal patterns, including hip movements, during the V1 and the V2 skating techniques. The findings showed that skiers gained potential energy prior to poling, before they transferred it to propulsion through the arms and poles during poling in V2, but not in V1.

- Clear differences between elite skiers, but high within-skier reproducibility of V2 hip movements.

- Validation of hip displacement estimated from accelerometer data and accelerometer data combined with gyroscope data during ski skating. The findings showed the highest external validity in the vertical direction. Intra-cycle rotation corrections increased validity, and using gyroscope data for this purpose gave an accuracy of < 8 mm in all directions for both V1 and V2.

- Validation of hip (S1) displacement for estimating COM displacement during ski skating. Sideways displacement was found valid, while upper-body and arm movements caused systematic differences in the antero-posterior and vertical directions during both V1 and V2.

- Indications that cycle time affects O_2-cost and performance in V2. The effect was small and likely, and this study represents the first time such a relationship has been shown at an individual level. Vertical acceleration also showed a small likely effect on O_2-cost and performance. This indicates that it is important to improve balance even in elite skiers.

- On-snow skiing differs from roller skiing even when inclination, speed, and rolling/gliding friction is controlled. The differences include altered hip rotation patterns, greater lateral hip displacement, longer poling times, and a tendency to smoother hip movements.

IMUs were easy to use in all situations without affecting the skier's technique. Combined with the unrestricted capture volume, IMUs are suitable for in-field movement-pattern registration. By comparing movement pattern features with established patterns, conclusions about a specific situation can be drawn. For instance, patterns from IMUs are very frequently used in the wider research area of automatic fall monitoring in elderly people (e.g. Pannurat et al., 2014). For such purposes, distinct differences in the pattern are most often used and therefore a modest accuracy is needed. This is also the case for sub-technique classification in cross-country skiing. To distinguish pattern differences, Sakurai et al. (2014; 2016) primarily used 1–3 Hz low-pass-filtered gyroscope data from wrists and roller skis, while Stöggl et al. (2014) used filtered accelerometer data from a smartphone located at the chest. Hence, using different types of heavy signal filtering, different IMU locations, and including different sensors are all possible methods for enabling good classification of sub-techniques (Table 2.5).

In the present thesis, we also aimed to recognize subtle differences in patterns, small differences between techniques and between skiers, relationships between performances and within-skier technique alterations, and differences caused by different equipment or conditions. To be effective, the method used for such measurements must be highly reproducible (internal validity), and therefore only modest filtering (i.e. 30 Hz low-pass) was used to retain detailed information in the IMU signals. Further, we aimed to determine whether IMUs could potentially be an "easy-to-use" alternative or supplement to more advanced and demanding technique analysis methods, in terms of quantifying movement patterns. Hence, the method also needs to produce valid results for acceleration, speed, displacement and rotation, in addition to accurate timing of technique features. First, internal and external validity of our methods will be discussed, before skiing-specific technique outcomes are discussed.

5.1 Internal validity

The papers included in this thesis show that IMU data, in addition to differentiating sub-techniques, are also reliable and suitable for assessing differences between skiers, determining the effects of different equipment and external conditions, and for providing individual feedback on alterations in a skier's technique. To reach these conclusions, two essential factors affecting reproducibility were considered: 1) Skiers' normal variation in movement, and 2) mounting (location and orientation) of the IMU between separate tests.

A skier's movement will always vary slightly from cycle to cycle. It was assumed that elite skiers have a more stable technique with less variation between cycles compared to lower-level skiers. Therefore, data were collected from elite skiers to test the reproducibility of the IMU method. To make sure the movement pattern represented the skier's fundamental technique, an average over several consecutive cycles was obtained. The rationale was that a number of cycles would lessen the impact of one irregular cycle. The findings in Study I showed that the method using six consecutive cycles with only accelerometer data was sensitive enough to reveal considerable between-skier differences and high within-skier reproducibility for elite skiers (Figure 4.1.1). Study III revealed that the method was also sensitive enough to detect longitudinal technique changes, along with changes in O_2-cost and performance at an individual level.

Different locations and orientations of the sensors will affect the IMU output (section 2.3). Because of different sensor locations, our S1 data was not directly comparable with either the upper chest data as obtained by Stöggl et al. (2014), or the upper-back data obtained by Marsland et al. (2012). Stöggl et al. (2014) remarked that their V2 pattern ("G3") was not symmetrical. This is in contrast to theoretical considerations of the V2 technique, and indicates that gravity was not aligned with the axis that the researchers had assumed to be vertically oriented in their smartphone (Stöggl et al., 2014). If this misaligned orientation is constant for each mounting of the sensor and within each test, the reproducibility will still be high (see section 5.2.1). However, if the orientation differs between tests, reproducibility is threatened. In Study I, we did not reveal different reproducibility between tests with and without remounting the sensor (tests four months or 20 minutes apart, respectively; Figure 4.1.1). Our findings also showed V2 to be a symmetrical technique (Figure 4.1.2). The difference compared to Stöggl et al. (2014) can be explained by the alignment procedure used. By using the constraint of constant speed, the IMU's horizontal plane was aligned with the global horizontal plane (Moe-Nilssen, 1998a). This made our method less vulnerable to inconsistent mounting of the IMU. However, there are two limitations: the restriction to constant speeds, which was also used to reduce drift in gyroscope data; and the assumption that the IMU's x-axis is, on average, parallel to the laboratory XZ-plane.

In Study IV, a calibration movement was included, based on the external validity findings in Study II. The calibration procedure was designed, at least in theory, to decrease the effect of variations in mounting and thereby increase internal validity. In Study II, the errors of IMU data estimating S1 movements were found to be larger in the horizontal plane compared to the vertical direction (Table 4.2). A heading misalignment angle (i.e. not fulfilling the assumption that the IMU's x-axis is on average parallel to the laboratory XZ-plane) will accentuate such errors. Using a numerical analysis, heading (Z-axis) misalignment angles of, on average, 2 (4) and 3 (1) degrees were found to minimize the errors in V1 and V2 techniques, respectively. For V1 and V2 respectively, correcting for these misalignment angles reduced the antero-posterior RMS error to 32 % (24 %) and 50 % (22 %) of the errors reported for IMU-G in Table 4.2. The calibration movement consisted of five hip flexion/extensions, and the procedure aligned the IMU's axes with the functional hip axis. Using this approach, the assumption is that the hip, on average, is oriented in the anterior direction, in cyclic movements at constant speeds. The effect of this calibration movement has not been validated.

Further, in Study IV, the treadmill test was performed in both the fall and the winter. This made consideration of internal validity possible (SD_w in Table 4.4). Without the repeated treadmill tests, comparisons between asphalt roller skiing and on-snow skiing would be speculative, and confidence in the differences found for on-snow skiing and treadmill roller skiing would have been reduced. Additionally, to ensure internal validity, the same uphill course was used both for roller skiing on asphalt and for on-snow skiing, and short trials were used to avoid fatigue affecting outcomes.

Finally, asymmetry between poles is well known in V1 (e.g. Smith et al. 1989, Nilsson 2004) but has not been previously reported in V2. In Study I we found a small asymmetry of 14 (17) milliseconds ($P < 0.01$) between pole liftoffs during the right compared to the left ski push (Paper I). It might be argued that this reflects poor reproducibility in our ground-contact temporal pattern method. However, as the asymmetry fits with the Z-axis rotational pattern shown in Figure 4.2.1 (i.e. positive angles when skier moves away from the right pole, but negative angles when the skier moves to the right), we argue that this indicates a methodological high sensitivity for revealing natural variations within the skier's movement. Hence, this asymmetry showed the high sample rate of IMUs to be an advantage for calculating ground-contact temporal patterns, compared to traditional video analysis.

5.2 External validity

Internal validity is a prerequisite for, but does not imply, good external validity. For many purposes, such as distinguishing between conditions or skiers, a reliable method is sufficient. However, we aimed to evaluate whether IMUs can contribute to quantifying movements and whether COM displacement can be accurately estimated from an IMU at S1. In this context, external validity is essential and aligning the IMU's axes with the global frame becomes a key factor. The IMU was positioned at S1 because S1 has been used in gait analysis (e.g. Moe-Nilssen & Helbostad, 2004; Floor-Westerdijk et al., 2012) and because cross-country skiing coaches focus on hip movement. The constraint of constant speed was discussed in section 5.1, while the effects of adjusting for intra-cycle rotations and the validity of estimating COM displacement from S1 data are discussed in sections 5.2.1 and 5.2.2, respectively. In principle, hip movement analysis can be performed without ground-contact temporal patterns. However, such temporal patterns include the technique parameters most frequently reported (section 2.6.1), the variables are useful for time-normalization of cycles, and for comparing signals with visual feedback from video. In addition, sub-techniques can be classified from IMU-revealed temporal patterns (Myklebust et al., 2011). Hence, the validity of our IMU-derived ground-contact temporal patterns is discussed in section 5.2.3.

5.2.1 Displacement of S1 – effects of intra-cycle rotations

Intra-cycle rotations cause a dynamic misalignment between the IMU axes and the laboratory reference frame of up to 20 degrees (Figure 4.2.1). This adds a fluctuating component of gravity to all three IMU axes. This misalignment particularly affects the measured acceleration in the horizontal plane, as sinus $\alpha > (1\text{-cosine } \alpha)$. This was confirmed by only the vertical direction displaying accuracy and precision < 10 mm when estimating S1 displacement without correcting for intra-cycle rotations (IMU-A method in Table 4.2). The intra-cycle rotations were found to be quite consistent among elite skiers (Figure 4.2.1). This was used in Study III, where gyroscope data were not available. Instead, intra-cycle rotations were adjusted using the rotation patterns from Study II (Figure 4.2.1). The method (IMU-A2) almost entirely removed timing errors in IMU data estimating S1 displacement, and removed 40%–75% of the RMS errors shown in the IMU-A method (Table 4.2).

Figure 5.2 illustrates acceleration patterns using the IMU-A (blue line), IMU-A2 (green line), and IMU-G (red line) methods for one skier. If the rotation patterns do not vary between tests, the effect of correcting for the rotations entirely affects external validity (difference between green and blue lines, assuming red line to be correct). However, some variation between cycles must be expected.

The differences between the green and red lines in Figure 5.2 indicate the amount of improvement when gyroscopes are included. Importantly, the hip rotation patterns during on-snow skiing in Study IV differed considerably from those seen in roller skiing (Figure 4.4). Hence, the rotation pattern used in Study III should not be used for on-snow skiing. It is appropriate for roller-skiing only, and presumably only if gyroscope data are not available. When combining accelerometer and gyroscope data (IMU-G), both accuracy and precision were improved, indicated by errors of only a few millimeters in all directions and in both sub-techniques (Table 4.2). Further, the effect of including gyroscopes for correcting intra-cycle rotations will theoretically be enhanced for skiers with less stable technique. Hence, combining accelerometer and gyroscope data is generally recommended as long as the amount of data is not restricted, or the aim is simply to distinguish two conditions.

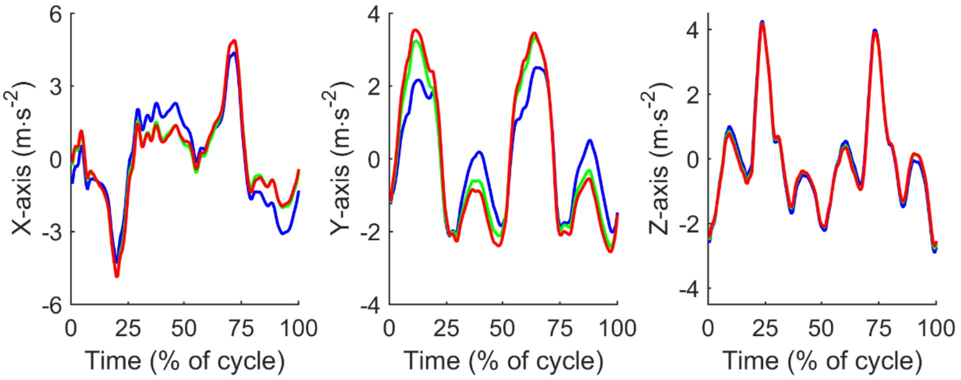

Figure 5.2 Acceleration curves for one skier. IMU-A (blue), IMU-A2 (green), IMU-G (red).

5.2.2 Estimated COM displacement

An IMU accurately measures the movements of the segment where it is attached (sections 2.3 and 5.2.1). Hence, the location of the IMU should be carefully considered according to the aim of analysis. Study II confirmed the hypothesis of Floor-Westerdijk et al. (2012) that more extensive use of limbs and the upper body would affect the accuracy of estimating COM from S1. Further, the different use of arms and upper body in V1 and V2 (i.e. asymmetry in V1 and different timing of poling related to ski pushoffs) can explain the different deviation between S1 and COM in the two techniques (Figure 4.2.2). Hence, the results in Study II indicate that arm and torso movements affect COM, but not S1. This implies that IMU data from S1 will not reflect technical changes affecting, for example, the arms, if the altered movement does not influence hip movements. Even though arm movements such as arm abduction/adduction will not greatly affect COM, they could still be important in terms of muscle fatigue, and hence affect performance. An IMU at S1 will therefore not be appropriate for such technique analyses.

For both the V1 and the V2 sub-techniques, sideways displacement of S1 was found to be valid for estimating sideways COM displacement. The 11% overestimation of sideways range of displacement in V1 (Figure 4.2.2), is probably related to the asymmetric use of the upper body in V1, measured as an ~20° Z-axis hip rotation during the poling phase (Figure 4.2.1). The estimates in antero-posterior and vertical directions had low external validity (Figure 4.2.2). However, high precision (i.e. small variations in RMS error) was found for S1 estimating COM displacement in all directions and both techniques. This indicates that the differences between S1 and COM displacements are highly systematic. Combined with large between-skier differences in COM range of displacement (Table 3 in Study II), this also indicates a sensitive method.

The errors revealed in antero-posterior and vertical directions inhibit exact calculation of energy fluctuations. However, a linear model for reducing the systematic sagittal-plane errors during V2 has recently been proposed and validated (Gløersen et al., 2015). In addition to translational movement of the hip in three directions, the model uses the torso angle (estimated from gyroscope data) for estimating COM displacement. The RMS errors between the model estimate and COM were 6 (2) and 8 (2) mm in antero-posterior and vertical directions, respectively (Gløersen et al., 2015). Hence, more than two thirds of the error in Study II was removed. This is encouraging for the development of an in-field measurement system. However, it must be noted that there are several issues to be considered. For example, the model still omits arm movements, and only elite skiers were used to fit the model at a single intensity. V2 is also frequently used on flatter terrains and speeds up to ~9 m·s^{-1} (Andersson et al., 2010; Sandbakk et al., 2011). If different intensities affect upper body movements differently, it might influence the precision of estimating COM using an IMU at S1.

5.2.3 Validity of ground-contact temporal patterns

In all studies, ground-contact temporal patterns were automatically quantified using single axis accelerometer data from poles and ski boots. Minor regulations of constraints were needed to avoid errors in some tests. Further, for about 1% of the pole plants the timing was too early or too late. The errors were < ± 0.1 seconds and comparable with the example in Figure 3.4. More errors (~2%) were found for on-snow skiing compared to roller skiing (Study IV). For all presented data, constraints were adjusted so that these errors were eliminated from affecting separation of cycles.

The small asymmetry in V2 (see section 5.1), together with the video (50 Hz) validation of pole and ski, hits and liftoffs (Table 4.1), show that IMUs with high sampling frequency (≥ 100 Hz) are well suited for calculating ground-contact temporal patterns. For this purpose, analyzing acceleration data seems sufficient, and a skating cycle can be divided into phases (Study III). However, the external validity of ski plants was less adequate. This is in line with a validation by Fasel et al. (2015), using a similar setup and a 200 Hz marker system as the reference. Detecting ski plants was even harder for on-snow skiing than for roller skiing (Study IV). Hence, ski plants were not emphasized in Study IV, and an alternative location of the IMU, another approach, or a different type of sensor is needed for accurate and precise timing of ski plants.

5.3 Ski skating technique considerations

Different external conditions (different *tasks*) affect the magnitude of the technique variables measured (section 2.2.1). Additionally, skiers have many degrees of freedom to improve their performance and there is considerable variation between skiers, even when they perform the same sub-technique under standardized external conditions (e.g. Figures 4.1.2, 4.2.1; Table 4.4). This makes assessment of technique quality a challenge. For example, the two skiers presented in Figure 4.1.1 have both succeeded internationally, but they have major differences in their movement patterns. The following sections discuss how the studies included in this thesis contribute to the understanding of ski skating technique. This includes differences found between V1 and V2 (section 5.3.1), technique alterations caused by different external conditions (section 5.3.2), technique variables found to relate to performance at an individual level (section 5.3.3), and technique specificity of roller skiing (section 5.3.4).

5.3.1 Sub-technique differences

Poling contributes to about two-thirds of the propulsion in V2, while less than half of the propulsion comes from poling in V1 (Smith et al., 2009). Studies I and II demonstrate that hip (S1) and COM vertical displacement during poling differ between V1 and V2 (Figure 4.2.2). In V2, the hip and COM are at their highest position just before pole plant and are lowered during poling, by gravity and active flexion in the hip and knees. This is similar to the COM pattern shown for double poling (Zoppirolli et al., 2015), and indicates that poling is accomplished to a large extent by the legs and trunk. The energy is re-directed from a downward to an anterior direction because of the pole angle. During the pure glide phase (ground contact for one ski only), a high starting position with new potential energy is gained by extension of the leg joints and repositioning of the arms and poles (Study III). In contrast, only minor vertical displacement of COM occurs during poling in V1, while on the side without poling, COM vertical displacement is more similar to V2 vertical displacement (Figure 4.2.2). Notably, there are also considerable differences between sub-techniques in terms of rotational patterns. For example, there are only minor changes in the forward (X-axis) tilt of the pelvis during poling in V1 compared to V2 (Figures 4.2.1). Further, studies I and II confirmed earlier findings of longer cycle time and cycle length in V2 compared to V1 (Nilsson et al. 2004, Smith et al. 2009). In summary, our setup of five IMUs showed clear differences between V1 and V2 in terms of hip acceleration, rotation, and displacement patterns, in addition to ground-contact temporal patterns (Figures 4.1.2, 4.2.1, 4.2.2).

5.3.2 Effects of inclination, speed, and friction on technique

As intensity is known to affect technique (section 2.2.1) the following discussion will describe how some of the technique parameters calculated for this thesis changed with inclination, speed, and friction. The included papers examined V2 at three different intensities (Table 3.1). In addition, unpublished data were collected during pilot tests over a wider range of intensities (3.5° – 8.0°, 3.0 $m \cdot s^{-1}$ – 5.0 $m \cdot s^{-1}$), using both the V1 and the V2 techniques. These data fit well with the overall movement patterns presented for both the V1 and the V2 techniques. Some unpublished data are included for discussion in this section.

Figure 5.3 is based on IMU data from pole accelerometers, as used in all four studies. With increasing speed, poling time decreases while reposition time is unchanged (Figure 5.3 left). In contrast, with increasing inclination, poling time is unchanged while reposition time decreases (Figure 5.3 right). The same effects were found for both V1 and V2, and the findings are supported in the literature (Millet et al., 1998c; Stöggl et al., 2011). Results from the constant speed and inclination trials in Study IV (8°, 3.0 $m \cdot s^{-1}$) also fit with the trend for inclination in Figure 5.3 (right). Altering friction affected cycle time through pure glide time (pole RT), but not poling time (pole PT) in Study IV (Table 4.4). Hence, skiers cope differently with acute changes in speed and inclination at submaximal intensities, and friction affects pole ground contact time in a similar way to inclination.

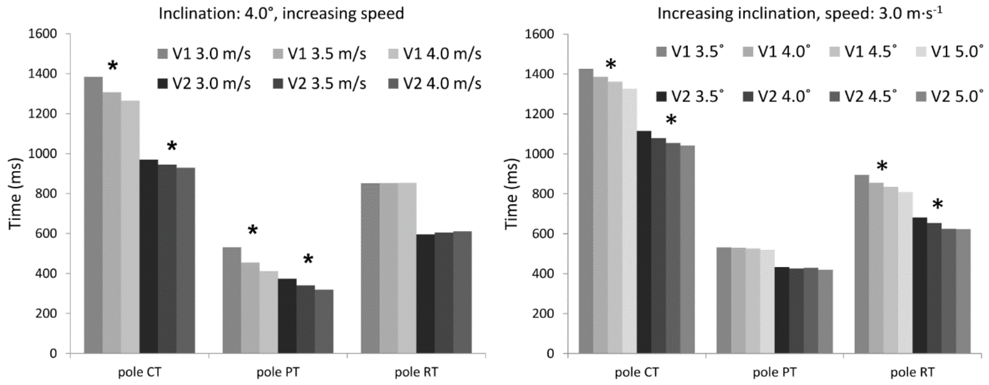

Figure 5.3. Pole cycle time (CT), poling time (PT) and reposition time (RT) during V1 (grey) and V2 (dark grey) at increasing speed (left, n=14, inclination: 4.0°) and inclination (right, n=11, speed: 3.0 $m \cdot s^{-1}$). * $P < 0.01$ between steps of speed/inclination. Unpublished data recorded by pole IMUs.

Friction force differences of around 7–18 N (20–100 W depending on speed) have previously been shown to affect O$_2$-cost (Hoffman et al., 1998), time to exhaustion (Ainegren et al., 2009) and maximum speed (Othonen et al., 2013). Study IV contributes to understanding the effect of friction while ski skating by revealing a positive correlation between performance time and on-snow friction (Paper IV, Figure 5). Even though the number of observations is low, the slope seems reasonable (Δ Time = $\Delta\mu \cdot 0.1508$ s). Breitschädel et al. (2012) reported essential friction coefficients separating the best skis to be as low as $\Delta\mu = 0.001$. By extrapolating our on-snow slope results this corresponds to the difference between gold and silver medals in the Falun World Championships 2015 in the 15 km skate (~18 seconds). Further, the on-snow slope fits well with the differences found for the roller-skiing time trial. The altered roller-skiing friction ($\Delta\mu \approx 0.015$; ~9–12 N; 27–36 W) resulted in an ~2.2 s (8% ± 3%) difference on the 128 m-long time trial.

At a fixed inclination and speed (8°, 3.0 m·s^{-1}), the skiers reduced their vertical displacement when the intensity was reduced by friction (Table 4.4). Cross-sectional comparison of Studies II, III, and IV indicated that vertical range of displacement was also altered by the angle of inclination (Table 5.3). As discussed above, friction seems to affect cycle time in the same way as inclination. Hence, inclination and friction seem to affect the same parameters of skiers' technique, at least in terms of pure glide time and vertical displacement.

Table 5.3. Cross-sectional comparison of hip range of displacement (ROD) along sideways (X), antero-posterior (Y), and vertical (Z) axis in the different studies.

		SD$_w$	Study II	Study III	Study IV
	Inclination		4.0°	6.0°	8.0°
	Speed		3.0 m·s^{-1}	3.5 m·s^{-1}	3.0 m·s^{-1}
	Friction		0.016	0.020	0.018
	External effect (W)		~177	~288	~346
	Skiers		Elite n=6	Elite n=13	Well-trained n = 9
ROD (cm)	X	2.6	39.0 ± 5.0	39.6 ± 5.9	38.6 ± 6.5
	Y	1.3	12.4 ± 0.7	13.2 ± 2.2	13.9 ± 2.4
	Z	0.6	10.1 ± 2.1	14.0 ± 2.1	15.7 ± 2.1

Note: group mean ± SD. SD$_w$ = within-skier SD based on the two treadmill tests in Study IV.

5.3.3 Essential V2 technique parameters

Increasing cycle length (i.e. cycle time · speed) is considered important for improving performance (e.g. Bilodeau et al., 1996; Stöggl & Müller, 2009; Sandbakk et al., 2010). However, one should be cautious when addressing feedback on single variables as cycle time. There are individual differences even among elite skiers (Losnegard et al., 2012b; Study I; Study III), and cycle time is strongly affected by the external conditions (section 5.3.2), which change constantly in cross-country skiing. Performing technique analyses at an individual level reduces the confounding factor of individual physiology and anatomical differences. *Cross-over* studies, for example examining the acute effects of inclination (e.g. Millet et al., 1998c), speed (e.g. Stöggl et al., 2011) or friction (e.g. Othonen et al., 2013; Study IV), or studies with *repeated measures* (e.g. longitudinal tests in Study III) are examples where the skier operates as his/her own control.

As the season progressed, the skiers in Study III reduced their time in the 1000 m time trial, O_2-cost, and movement patterns as indicated by reduced RMS accelerations. At the same time the skiers increased their poling time and pure glide time (Paper III, Table 1). The most obvious reason why the performance improved in the winter is that the test was conducted close to the main events of the season and the skiers tried to peak their performance for these. Better physical condition might theoretically alter skiers' technique in some way. Hence, causal relationships between technique parameters and performance cannot be drawn from such a longitudinal repeated measures design without cautions. However, the mixed model adjusted for the overall changes over time (see section 3.5.1). Since there was still a relationship between altered cycle time and O_2-cost after the adjustment, this indicates a small likely effect of cycle time, or more precisely poling and pure glide time, on performance (Table 4.3). Figure 4.3 illustrates the amount of the seasonal change in O_2-cost and the amount that the technical variables accounted for. A relationship between cycle time and performance has not previously been shown at an individual level for the V2 technique. Leirdal et al. (2013) used a cross-over design, but did not find any effect on O_2-cost by acutely altering frequency (cycle time). It is plausible that longitudinal adaptations are more functional and have different effects compared to acute forced alterations in technique.

The definition of acceleration (change in velocity / time) shows that there is a link between acceleration and time, and time to perform a non-linear movement will directly affect the amount of acceleration. Additionally, the acceleration measured by an IMU reflects the resultant of force impulses affecting the IMU. The force impulses result from muscle contractions, which have a metabolic cost. Hence, a positive relationship between change in O_2-cost and change in hip acceleration is logical. Further, if the hip displacement is identical, metabolic cost and time will be negatively related. This is in line with the findings of Zoppirolli et al. (2015), who found longer double-poling cycle-time and reduced vertical displacement of COM to be related to high-level skiers' superior O_2-cost compared to slower skiers (Zoppirolli et al., 2015). In Study III, negative and positive relationships with altered O_2-cost were found for cycle time and vertical acceleration, respectively. Hence, a slow smooth movement with low vertical acceleration seems favorable in terms of O_2-cost and performance.

Notably, vertical acceleration in the latter part of the gliding phase ("middle pure glide"), affected O_2-cost and performance to the same extent as the full-cycle vertical acceleration (Table 4.3). During this part of the glide phase, one ski is the only contact point with the ground. Hence, this reduced acceleration indicates a smoother coordination of movements and improved balance. The possible performance-enhancing implications of better balance are: (1) sufficient time for, and less energy-demanding repositioning of segments and equipment; (2) longer time for recovery of propulsive muscles; and (3) possibly reduced friction on snow due to a flatter oriented ski (Study IV).

5.3.4 Training specificity

More than half the time, elite skiers perform sport-specific training (Losnegard et al., 2013; Sandbakk & Holmberg 2014). In the summer that means asphalt roller-skiing. When performing roller skiing training, elite skiers aim to simulate on-snow skiing technique and do not try to achieve an optimal roller-ski skating technique (Losnegard et al., 2012b). However, some cross-country skiers clearly perform better in roller skiing competitions than in on-snow competitions, implying that there are some differences between roller-skiing and on-snow skiing. In terms of technique, Gervais & Wronko (1988) found differences for the marathon-skate technique in on-snow skiing compared to outdoor roller skiing on "new skating-specific roller-skis". However, both equipment and sub-techniques have changed markedly since then. Hence, Study IV provides novel information about training specificity in cross-country skiing by providing the first direct comparison between modern roller-skiing and on-snow ski skating techniques.

Despite the differences in ground surface and air resistance, neither different ground-contact temporal patterns nor hip movement pattern differences were found between indoor (treadmill) and outdoor (asphalt) roller skiing. This indicates that treadmill roller-skiing tests with controlled laboratory settings are valid for evaluating cross-country skiers' roller-skiing technique. Further, the finding of large to very large correlations for ground-contact temporal patterns and generally similar overall hip movement patterns between roller skiing and on-snow skiing indicates roller-ski skating to be a good simulation for on-snow ski-skating. However, compared to roller skiing, on-snow skiing involves altered hip rotation patterns, greater lateral hip displacement and increased poling times, and we also found a tendency to smoother hip movements (Figure 4.4 and Table 4.4).

The non-significant effect of "adding" air resistance (asphalt vs. treadmill) implies that the differences between on-snow skiing and roller-skiing techniques may only be caused by different mechanical properties of the skis and/or by ground surface properties (Baumann, 1985). On-snow skis are almost three times longer than roller skis, which influences their inertial properties. On-snow skis are also more flexible and, in study IV, 14% (120 grams) lighter than roller skis. Additionally, the binding hinge was positioned ~4.5 cm further in front of the ski's center of mass for roller skis compared to on-snow skis. The position of the pivot hinge between ski and boot has been shown to influence coordination of muscle activity (Bolger et al., 2014). Hence, the skis and roller skis used in these tests differed in several ways.

Since similar friction coefficients were obtained (Table 4.4), different rolling/gliding friction could not explain the differences between on-snow skiing and roller-skiing techniques. However, an inward-tilted ski will most likely dig into the snow and thereby increase ploughing and friction, as shown for speed skating on ice (Lozowski et al., 2013). In contrast, an inward-tilted roller-ski does not increase roller friction (Sandbakk et al., 2012a). Hence, skiers may try to avoid this disadvantage while on-snow skiing by keeping a flatter ski. A flatter ski may be achieved by standing more directly above the ski. Such a position would lead to a larger lateral hip range of displacement, as found for on-snow skiing (Table 4.4). A wider ski angle, which alters the distribution of propulsion between arms and legs (Smith et al., 2009), would also lead to a larger lateral hip range of displacement (Sandbakk et al., 2013a).

Notably, the longitudinal results in Study III indicated only minor technique alterations in cycle time and vertical acceleration between June and August, but larger alterations from August to October and from October to January. While all tests were performed on the treadmill, the skiers' training between tests gradually changed from only roller skiing to only on-snow skiing. Whether, or to what extent, the increased amount of on-snow skiing influenced the results in Study III is highly speculative. However, both cycle time and vertical acceleration were altered by acute change of skis in Study IV. Unfortunately, Study IV was not designed to assess which of roller skiing or on-snow skiing techniques are beneficial in terms of cross-country skiing performance. The study was not designed to assess which of surface hardness or mechanical ski properties caused the differences between on-snow skiing and roller-skiing techniques. Hence, we do not know the impact of the differences found in Study IV. However, the differences were clear, and the hypothesis that there are only trivial differences between on-snow skiing and roller skiing if the same skiers are tested at equal inclination, speed, and friction failed.

6.0 Conclusions

Using IMUs allowed for easy data collection, and revealed highly detailed and reproducible hip movement patterns in all four studies. Limb-mounted IMUs provide a precise and simple way to perform ground-contact temporal analyses, except for estimating the timing of ski plants. Additionally, the following hypotheses were **confirmed**:

H1 *Movement patterns captured by IMUs differ systematically between sub-techniques (V1 and V2) and skiers, but are reproduced within skiers.*

Comment: The sub-techniques showed well-defined patterns of limb ground-contacts and of hip acceleration, speed, displacement, and rotation. The clear hip lowering during poling in V2, but not in V1, allows potential energy gained prior to the poling thrust to be transferred to propulsion through the arms and poles.

H2 *Methods adjusting for intra-cycle hip rotations increase the accuracy and precision of estimating hip (S1) displacement from IMU data in both V1 and V2.*

Comment: Including both accelerometer and gyroscope data is recommended. Using both sets of data produced RMS accuracy and precision < 8 mm in all directions.

H4 *IMU data can quantify essential technique alterations affecting work economy and performance of elite skiers.*

Comment: Small likely effects on performance were found for both cycle time (poling time and pure glide time) and RMS vertical acceleration.

The following hypotheses **failed**:

H3 *Errors between S1 and COM displacement are small, systematic, and negligible in both V1 and V2.*

Comment: Sideways COM displacement was accurately estimated by S1 displacement, but there were large systematic deviations in the vertical and antero-posterior directions. Hence, the hypothesis failed based on Study II. However, new models have been shown to greatly reduce the errors for the V2 technique.

H5 *There are only trivial differences between roller skiing and on-snow skiing techniques.*

Comment: The hypothesis failed because on-snow skiing altered hip rotation patterns, resulted in greater lateral displacement, longer poling times, and a tendency to smoother hip movements compared to roller skiing.

7.0 Perspectives and directions for future research

This thesis has shown that IMUs can be useful when comparing different conditions, skiers, and even when evaluating improvements in ski-skating technique at an individual level. This implies that other situations can be compared as well. Technical changes associated with the development of fatigue have been analyzed using an IMU during running (le Bris et al., 2006). A similar comparison could easily be conducted using IMUs during cross-country skiing. Another line of enquiry based on our findings is whether longer roller-skis and/or adjusting the binding position would better simulate on-snow skiing technique, and whether this makes a considerable impact on performance.

In terms of validity, the S1 method for estimating COM needs to be improved to estimate energy fluctuations. In this respect, the model presented by Gløersen et al. (2015) should be tested at different intensities using skiers at different levels of performance. Further, the IMU method used in this thesis could just as well be used in other sports, as long as the movements are cyclic and the average COM velocity is constant from cycle to cycle. These constraints are the main limitations of the method used in this thesis. The constraint of constant speed was used to align the IMU with the global coordinate frame and to adjust for drift in gyroscope data. This was necessary to attain high internal and external validity. A similar method might be just as valid for acceleration and deceleration phases if the instantaneous speed is known. Incorporating GNSS data might be one alternative for this purpose.

An automatic algorithm for sub-technique classification would reduce time for section-time analyses and help skiers optimize their training by quantifying the amount of training in each specific sub-technique. However, there have been some challenges related to correct classification of turns (Marsland et al., 2015; Sakurai et al., 2016) and timing of technique transitions (Stöggl et al., 2014; Sakurai et al., 2016). Therefore, the results presented in this thesis, which show many features describing V1 and V2, may contribute to the development of an even better automatic algorithm for sub-technique classification and detection of sub-technique transitions.

The limb accelerometers used in the included studies were wired to the data acquisition unit on the hip. A methodological future step would be to get rid of these wires. Streamlining the algorithms could also permit immediate feedback to the skier. The presented data show that many features differ between skiers. The challenge is the lack of knowledge about what contributes to technique quality, which parameters to focus on, and how to optimize technique at an individual level. To extend this knowledge, an immediate feedback system and longitudinal data would probably make a considerable impact. The effect of feedback on motor learning is also a huge research field where treadmill roller-skiing could contribute.

8.0 References

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Paper I

Myklebust H., Losnegard T., Hallén J.

Differences in V1 and V2 ski skating techniques described by accelerometers.

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Differences in V1 and V2 ski skating techniques described by accelerometers

H. Myklebust, T. Losnegard, J. Hallén

Norwegian Research Centre for Training and Performance, Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway
Corresponding author: Håvard Myklebust, Department of Physical Performance, Norwegian School of Sport Sciences, 0806 Oslo, Norway. Tel: +47 99 41 24 63, Fax: +47 22 23 42 20, E-mail: haavard.myklebust@nih.no

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The aims of the study were to describe the differences between the ski skating techniques V1 and V2 and evaluate reproducibility in complex cyclic hip movements measured by accelerometers. Fourteen elite senior male cross-country skiers rollerskied twice for 1 min (V1 and V2) at 4° inclination and 3 m/s. Tests were repeated after 20 min and again 4 months later. Five triaxial accelerometers were attached to the subject's hip (os sacrum), poles, and ski boots. Post-processing included transforming to an approximately global coordinate system, normalization for cycle time, double integration for displacement, and revealing temporal patterns. Different acceleration patterns between techniques and large correlation coefficients (Pearson's $r = 0.6$–0.9) between repeated trials were seen for most parameters. In V2, the hip was lowered [–10.9 (1.2) cm], whereas in V1, the hip was elevated [4.8 (1.5) cm] during the pole thrust. In conclusion, V2 but not V1 showed similarities to double poling in the way that potential energy is gained between poling strokes and transferred to propulsion during the poling action. Elite skiers reproduce their own individual patterns. One triaxial accelerometer on the lower back can distinguish techniques and might be useful in field research as well as in providing individual feedback on daily technique training.

Ski skating is a complex cyclic technique where both arms and legs produce the propulsive forces. The degree of freedom to choose different movement patterns is large as there are no tracks or hindrances that guide movement (Smith, 2002). Hence, different techniques have evolved with, for instance, different timing between arms and legs. During ski skating, the ski reaction forces are approximately perpendicular to the ski surface with the ski angled with respect to the forward direction and the ski edged with respect to the snow surface (Smith, 2002). Both of these angles can vary but are normally rather small, meaning that the propulsive force becomes only a fraction of the force applied by the skier on the ski. Hence, forces produced by the legs are relatively ineffective (Smith et al., 2009). The forces applied through the arms and poles are also at an angle to the forward direction but the angles are more favorable, meaning that more of these forces are translated into propulsive forces (Smith et al., 2009). Biomechanically, it is therefore an advantage to put most emphasis on the poling movement. However, physiologically the legs have a larger muscle mass and are much stronger and it has been shown that even during double poling, a ski technique where no propulsive forces are produced by the legs, the legs are the largest oxygen consumer (Calbet et al., 2005). It has been shown that this is because the poling is not only accomplished by the upper body (arm, shoulder, and the trunk muscles), but also by active movement of the hip and knee joints (Holmberg et al., 2005). Hence, the arms and legs are not working independently but must be timed correctly to produce the most effective propulsion.

The most common ski skating techniques are V1 (also named "paddle dance," "offset," and "gear 2;" Nilsson et al., 2004) and V2 (also named "double dance," "one skate," and "gear 3;" Nilsson et al., 2004). These two techniques have different timing between pole and ski movements. The V1 technique is generally considered to be an uphill technique characterized by asymmetrical use of the upper body in one asynchronous double-poling action per cycle time (CT) with one of the skating strokes ("strong side"). In contrast, the V2 technique is symmetrical in that there is one synchronous double-poling action with each skating stroke. Studies of these complex movement patterns with fixed infrared camera systems combined with the direct linear transformation method (Smith et al., 2009) provide three-dimensional analysis with position, speed, and acceleration of center of mass, joints, limbs, and equipment. Ordinary two-dimensional kinematic analysis has also been combined with kinetic analysis of goniometers and pole and ski force measurements during roller skiing on treadmills

(Smith et al., 2009) and outdoor on asphalt (Street & Frederick 1995; Millet et al., 1998a, b) as well as during skiing on snow (Stöggl et al., 2008, 2010). These traditional approaches are both time consuming and limited to research in a laboratory or only during small parts of courses outdoor on snow. Small accelerometers based on inertial sensors can easily be mounted on skiers without affecting their movements and can collect data for longer periods. Accelerometers have frequently been used in gait analysis (e.g., Moe-Nilssen 1998a, b; Hanlon & Anderson 2009; Hartmann et al., 2009), but to our knowledge there are only a few studies in the literature using accelerometers in cross-country (XC) skiing. van den Bogert et al. (1999) used triaxial accelerometers to calculate forces at the hip joint in different activities including XC skiing, but did not analyze the movement pattern in detail. Myklebust et al. (2011) showed how temporal patterns can be extracted from accelerometers mounted on poles and ski boots and further used for detecting technique transitions when XC skiing outdoor on snow. Marsland et al. (2012) visually identified different cyclical movement patterns in different XC skiing techniques by placing a commercially available microsensor system on skiers' upper backs and using highly smoothed data (2 Hz low-pass cutoff frequency). However, they did not control for speed, inclination, or snow conditions and individual differences might have been partly due to different placement of the sensor system.

The aim of this study was to describe differences between techniques, V1 and V2, in terms of hip acceleration and to evaluate whether individual skiers reproduce their hip acceleration patterns during roller ski skating within one run from cycle to cycle, between runs on the same day, and after 4 months' preseason training. To study this, elite skiers performed treadmill roller skiing at one constant inclination and speed in June (both techniques) and October (V2 technique only). We hypothesized that V1 and V2 give distinct different patterns that can be recognized in each individual skier. Further, we hypothesized that the acceleration pattern varies significantly between skiers but that skiers reproduce their individual pattern within and between runs.

Materials and methods

Subjects and ethical approval

Fourteen elite senior male XC skiers [23.9 (3.0) years, 182 (5.2) cm, 76.2 (7.9) kg, VO_{2max}: 76.2 (4.8) mL/kg/min or 5.8 (0.5) L/min] volunteered to participate in the study in June. Eight of the skiers were retested in October. All skiers had top 30 rankings in the Norwegian championship and 7 of them had top 15 ranking in the International Ski Federation World Cup races. All skiers were familiar with testing on a roller ski treadmill and gave their written consent before study participation. The regional ethics committee of southern Norway approved the study.

Experimental setup and data collection

Using medical tape, triaxial accelerometers were adhered directly to the "hip" (os sacrum – S1), poles (10 cm below handgrip) and ski boots (heel). After an 8-min roller skiing warm-up, data were collected during a 1-min trial in each of the two different skating techniques, V1 and V2. The speed and inclination of the treadmill were constant (3.0 m/s and 4°) at a load where both techniques are normally used (Andersson et al., 2010). Losnegard et al. (2012) reported no differences in physiological responses (O_2 cost, heart rate, blood lactate) or perceived exertion between V1 and V2 at these loads (external power ~200 W). Details of the treadmill, poles, and roller skis are described in Losnegard et al. (2012).

There was a 2-min rest between the two trials, which were videotaped with a 50-Hz stationary camera (Sony DCR-TRV900E, Sony, Tokyo, Japan), placed perpendicular to the skiing direction at a distance of 5 m. Thirteen seconds of acceleration and video were recorded simultaneously and synchronized with syncPlux (pluX, Lisbon, Portugal) for validation of two-dimensional hip displacement and the hits and liftoffs identified automatically by the accelerometers (see below).

After the two trials, the subjects continued with a routine testing procedure and after 20 min of stepwise increasing submaximal skiing (Losnegard et al., 2012), a new set of accelerometer and video data were collected (V2 only) at the same inclination and speed as before. The routine testing procedure was repeated 4 months later and a new set of data were collected for V2. Hence, three sets of V2 data were collected at the same inclination and speed to evaluate the skiers' ability to reproduce their technique on the same day and after 4 months of normal season preparation. One set of V1 data was collected to compare hip movements and temporal patterns between the two skating techniques.

Accelerometers

The system mounted on the skiers weighed only 140 grams in total. The outer dimensions of the accelerometers were ~1.0 × 2.0 × 0.5 cm (xyzPLUX, pluX), and the range of measurement was ±4.5 g. The accelerometers weighed 11 grams each including cables to the 12-bit data acquisition system (bioPLUX research, pluX). The bioPLUX unit weighed 85 grams, was located at the hip, and included a battery and a Bluetooth transmitter. All five accelerometers used were similar, but the pole and ski boot accelerometers were only used for analyzing timing of the pole and ski ground contact hits and liftoffs (see below). Therefore, only data for acceleration in one direction, aligned with the length of the pole (pole sensors) and perpendicular to the ground (heel sensors), were collected. Accelerometer data were acquired at 1000 Hz, transmitted in real time via Bluetooth to a computer, and saved by MonitorPlux 2.0 (pluX).

Data analysis

The accelerometer data were post-processed using Python 2.5.4 (Phyton Software Foundation, Beaverton, Oregon, USA)[1] with the "numpy"[2] and "scipy"[3] packages. Algorithms were developed to automatically detect the plant and liftoff of each ski and pole ground contact using the four uniaxial pole and heel signals. Triaxial data from the hip were transformed to an approximately global coordinate system, defined to be positive for sideways (Side), antero-posterior (AP), and vertical (Vert) directions on a flat treadmill from weak to strong side, forwards, and upwards, respectively. In V1, the skiers freely chose their strong side, left or right. In V2, the right side was always defined as the "strong side." To compare patterns between runs, subjects, and techniques, data were time normalized to one cycle (100%) that was defined to be from one strong side ski liftoff to the subsequent strong side ski liftoff (Fig. 1).

[1] http://python.org

[2] T. Oliphant, 2006 (http://numpy.scipy.org)

[3] T. Oliphant, 2007 (http://scipy.org)

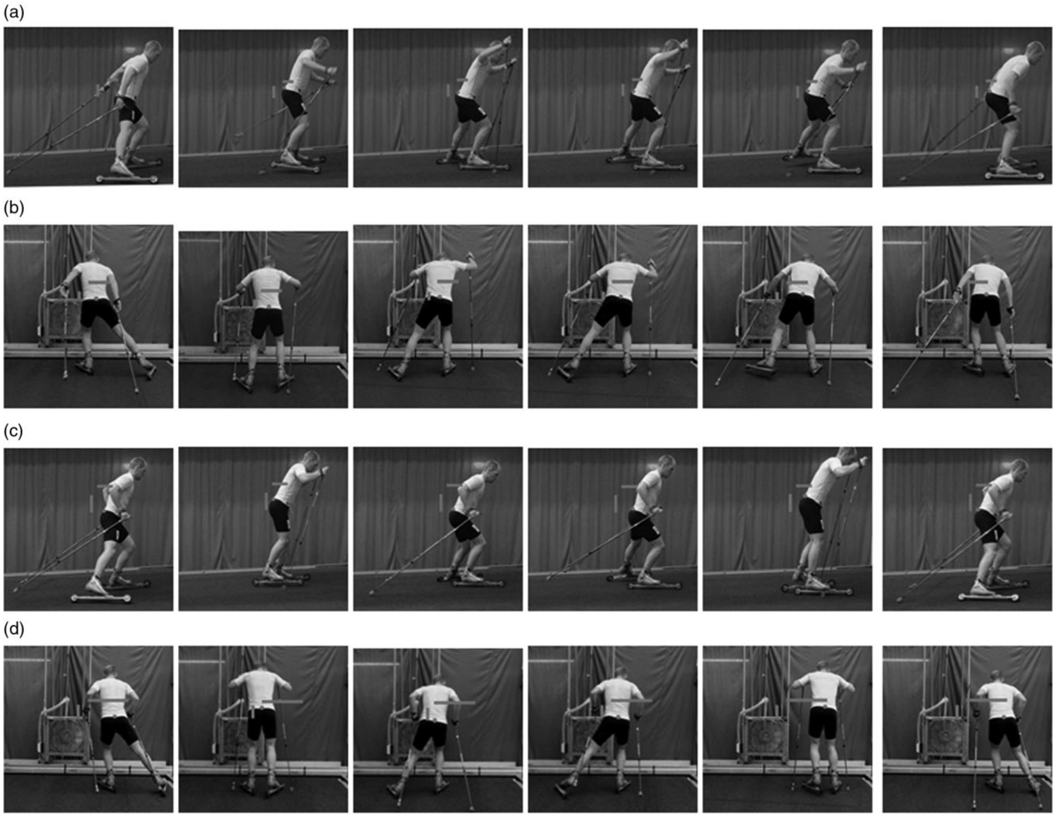

Fig. 1. One cycle of V1 (a, b) and V2 (c, d) is shown. The dot indicates where the hip (os sacrum) accelerometer is located, and the bars indicate the range of displacement of the sensor during one cycle.

A second-order low-pass filter with a cutoff frequency of 30 Hz was applied to all voltage signals. The voltage signals were then converted to acceleration in *g*-units using accelerometer-specific calibration constants and the formula:

$$g\text{-value} = \frac{raw\ signal - zero\ signal}{1g\ signal - zero\ signal}$$

where all values on the right side of the equation are millivolt values. The calibration constants were acquired from slow rotation of the sensors through the three axes. The maximum voltage in each direction during this procedure was set to 1 *g*, the minimum voltage was set to −1 *g*, and the zero signal was set as the mean of the two constants. The calibration constants were fine-tuned to fit the assumption that

$$x^2 + y^2 + z^2 = 1.0^2$$

where *x*, *y*, and *z* are the local coordinates of the accelerometer in each of six random static positions in a procedure similar to the method of Lai et al. (2004). To reduce the computer power needed for CT normalization of the hip data, the resolution was reduced from 1000 to 200 Hz by sampling every fifth value. Timing of strong ski liftoff was defined as the start of each normalized cycle, which consisted of four samples per percentage using a third-order interpolation between known points (≈280 in V1 and ≈385 in V2). The curves representing each subject are an average of six (one) subsequent cycles from the 13 s recorded.

Pole and ski plants and liftoffs validation

A combination of jerk (first derivative of raw acceleration), span (second derivative of raw acceleration), and highly smoothed acceleration were used to detect time points for pole and ski plants and liftoffs. The time points were validated against video (50 Hz) using Dartfish Connect 4.5.2.0 (Dartfish, Fribourg, Switzerland). Seven (V1) or six (V2) cycles from two trials in each technique from six randomly selected subjects were used for validation. Only the right pole was analyzed, resulting in a total number of 84 poles and 168 ski plants and liftoffs in V1. In V2, 144 plants and liftoffs were analyzed for both poles and skis.

Accelerometer vs center of mass displacement

Six of the subjects were randomly selected for two-dimensional video (25 Hz) analysis of both techniques. The mass centers of 16 segments were located during four subsequent pole pushes using the open-source program Tracker 4.751 (http://www.opensourcephysics.org). The body's center of mass was calculated using Tracker 4.751 based on each segment mass that was individually estimated based on height and weight (Zatsiorsky &

Seluyanov 1983). Also, the hip accelerometer was located on the video and displacement was measured to compare hip accelerometer displacement with center of mass displacement.

Calculated timing parameters

CT was defined as the time between strong ski liftoffs and cycle rate (CR) as CT^{-1}. Cycle length (CL) was calculated as treadmill speed divided by CR. Temporal patterns were based on the timing of pole and ski plants and liftoffs. Push time (PT) was defined as time between a ski plant and subsequent liftoff, and recovery time (RT) as time between liftoff and subsequent plant. Poling CT, PT, and RT were calculated the same way based on poling events. If not otherwise mentioned, the pole CT, PT, and RT are the mean of both poles during a full cycle. Synchrony between poles was calculated as time for right pole event minus time for left pole event, giving a negative value if the left pole event occurred after the right pole.

Aligning accelerometer axes to an approximately global coordinate system

The hip accelerometer was adhered with local axis approximately aligned to the global axis in a neutral standing position. Because of the constant treadmill speed, it was assumed that mean accelerations in the Side, AP, and Vert directions over the collected cycles were zero when gravity (≈1.0 *g*) was subtracted from the vertical direction. The following equations were used to meet the assumption and estimate the average tilt angles:

$$0 = mx \times \cos B \times \cos C - my \times \sin C + mz \times \sin B \quad [1]$$

$$0 = my \times \cos A \times \cos C - mz \times \sin A + mx \times \sin C \quad [2]$$

$$0 = mz \times \cos A \times \cos B - mx \times \sin B + my \times \sin A - mABS \quad [3]$$

where *mx*, *my*, and *mz* are the mean values of acceleration in each local accelerometer direction; *A*, *B*, and *C* represent average tilt angles of the local accelerometer around to the global axes; and

$$mABS = \sqrt{mx^2 + my^2 + mz^2} \quad [4]$$

The angles *A*, *B*, and *C* were found by solving the equations numerically with Newton's method. False solutions were excluded if reversing signals from eqns. [5–8] (see below) failed to match the original values used in eqns. [1–3]. Angle *A* showed a group mean of −27° (forward tilt), whereas angles *B* and *C* were <2° compared with the global axes. Most of the intersubject differences [standard deviation (SD) <6°] came from different alignments when affixing the accelerometer and a very strong correlation ($r > 0.94$) was seen between tilt angles in the runs on the same day.

We also adjusted for the average tilt angles and calculated the local Side, AP, Vert, total, and resultant accelerations for each normalized time point in each cycle, based on these equations:

$$Side_i = x_i \times \cos B \times \cos C - y_i \times \sin C + z_i \times \sin B \quad [5]$$

$$AP_i = y_i \times \cos A \times \cos C - z_i \times \sin A + x_i \times \sin C \quad [6]$$

$$Vert_i = z_i \times \cos A \times \cos B - x_i \times \sin B + y_i \times \sin A \quad [7]$$

$$Total_i = \sqrt{Side_i^2 + AP_i^2 + Vert_i^2} \quad [8]$$

$$Resultant_i = \sqrt{Side_i^2 + AP_i^2 + (Vert_i - mean\ Vert_i)^2} \quad [9]$$

where *x*, *y*, and *z* are the raw signals from the triaxial hip accelerometer at each time point i of each cycle; *A*, *B*, and *C* are the average tilt angles found from eqns. [1–3]; and mean Vert ≈1.0 *g*. If we assume no rotation of the hip (away from the average tilt angles) during each cycle, the global accelerations equal the accelerations from eqns. [5–9]. This is of course a simplification, but because the procedure was used the same way for all subjects with all collected data, the local accelerations were suitable for comparing athletes and techniques as well as individual reproducibility between cycles and runs.

Speed and position of the hip

Integrating acceleration gives speed and integrating speed gives position, but initial acceleration and speed at the onset of each cycle are not zero. Because of the constant treadmill speed and the fact that the subject, after each cycle, returns to approximately the same location on the treadmill, the average acceleration, speed, and distance over the recorded cycles are all approximately zero. Hence, subtracting the mean value when integrating the normalized acceleration or speed curve gives the speed and position relative to the origin on the treadmill:

$$Speed_i = \int_0^i acceleration\ dt + C \quad [10]$$

$$Position_i = \int_0^i acceleration\ dt + CC \quad [11]$$

where *dt* is the real-time interval for each percentage of the cycle at each time point *i* and

$$C = -mean \int acceleration\ dt \quad [12]$$

$$CC = -mean \int speed\ dt \quad [13]$$

Displacement was defined as the distance away from the mean position on the treadmill at each time point i:

$$Displacement_i = position_i - mean\ position \quad [14]$$

Accumulated distance shows how far the hip has traveled during one cycle:

$$Accumulated\ distance_D = \int_0^{100} absolute\ speed_D\ dt \quad [15]$$

where D is one of the directions sideways, vertically, AP, or the resultant direction.

Reported parameters

From the pole and ski accelerometers we reported the calculated parameters CR, CL, CT, PT, RT, synchrony of poles, and normalized temporal patterns (shown in figures only). We also determined individual and group mean curves, group mean maximum and minimum acceleration, accumulated distance, and range of displacement in each of the three directions. Maxima and minima were taken from each subject's mean hip acceleration curve.

Statistical analysis

All data are presented as mean and SD. Two-sided paired *t*-tests were used for detecting statistical differences between techniques, and between strong and weak side in the synchrony parameter. Analysis of variance with Bonferroni correction was used to compare the mean values of the three runs in V2. The magnitude of differences was expressed as standardized mean differences [Cohen's *d* effect size (ES)]. The criteria to interpret the magnitude of the ES were 0.0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and >2.0 very large (Hopkins et al., 2009). Typical error and Pearson's coefficient of regression values are presented for reproducibility of the hip acceleration parameters between the trials on the same day. A correlation coefficient >0.5 is named "large" (Hopkins et al., 2009). Statistical calculations were performed with Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and SigmaPlot 11.0 (Systat Software Inc., San Jose, California, USA). A *P*-value ≤0.01 was considered statistically significant.

Results

Validation and comparison of hip and center of mass displacement

All pole and ski plants and liftoffs were automatically detected by the program. No significant differences between program-identified and manual video-identified time points were found (Table 1). The largest systematic shifts and random variations (SD) between methods were found for ski plants. This was partly due to unclear impacts and difficulties in identifying time points for ski plants in the video. Video analysis revealed that hip displacement approximated center of mass displacement in the vertical direction in both V1 and V2, but in the forward direction only for V1 (Fig. 2).

Table 1. Time difference (ms) between features detected automatically in the program and manually from video analysis. Positive value means video detects the event before the program

	Pole plant	Pole liftoff	Ski plant	Ski liftoff
V1 (*n* = 84 or 168) (ms)	9 (34)	−13 (27)	39 (56)	6 (31)
V2 (*n* = 144) (ms)	6 (37)	−12 (25)	47 (74)	−1 (23)

Values are mean (standard deviation); data from six subjects, two trials per subject in each technique, six (one) cycles per trial. Only the right pole was analyzed.

Reproducibility

Similar hip acceleration patterns in the three directions and in both techniques were found in all skiers, but there were also some obvious individual variations (Figs. 3 and 4). The skiers reproduced these individual patterns during one run (Fig. 3) and between two runs on the same day (Table 2), as well as between runs 4 months apart (Fig. 4). The intersubject variation was 3%, 29%, and 26% larger than the intrasubject variation in Side, AP, and Vert directions, respectively. Hence, in elite skiers, there are some consistent individual differences in movement patterns that can be detected with one triaxial accelerometer on the hip.

There were no group mean differences between runs (the same day or 4 months apart) in the pole and ski timing parameters or for the hip acceleration parameters including maximum and minimum acceleration, range of displacement, and accumulated distance in the different directions. Minimum AP acceleration showed the highest retest correlation coefficient ($r = 0.94$), and most of the test parameters had large correlations between the two runs in June (Table 2).

Differences between techniques

The main difference between the two techniques is that in V2 the poles are used for every leg push-off as

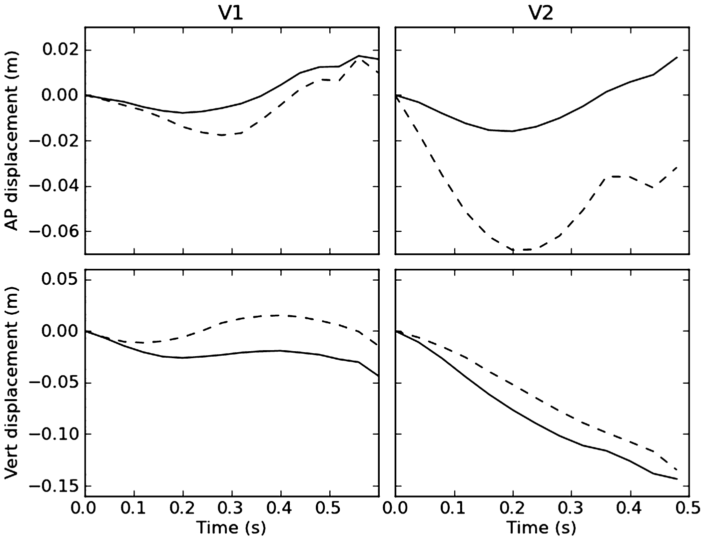

Fig. 2. Displacement of center of mass (solid lines) and hip accelerometer location (dotted lines) from two-dimensional video analysis during pole thrusts (in each technique: subjects = 6, thrusts per subject = 4, thrusts in total = 24). AP, antero-posterior; Vert, vertical direction.

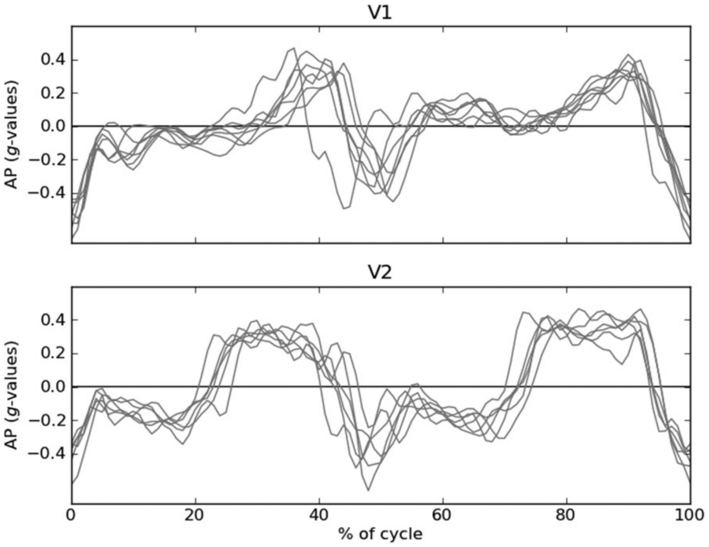

Fig. 3. Within-run reproducibility of hip acceleration in antero-posterior (AP) direction for one representative subject in V1 (upper panel) and V2 (lower panel). Each line represents one cycle.

opposed to every second leg push-off in V1. Hence, the CR and the poling CR (pole CR) is the same in V1, whereas the pole CR is double the CR in V2. CR was lower and CL was longer in V2 than in V1, but pole CR was higher in V2 as a result of both shorter pole PT and RT (Table 3).

During V2, the inner pole[4] in each thrust had a minor but significantly longer ground contact time than the outer pole[5] due to a 0.007 (0.014) s later liftoff (no difference in pole plants). V1 showed the opposite. The outer pole (strong side) showed a 0.05 (0.05) s longer PT than the inner pole (weak side), also due to delayed pole liftoffs ($P < 0.01$; Table 3).

For each poling action, pole PT was shorter in V2 than in V1, but because of the double action in each cycle, the total PT during a full cycle was longer in V2. Pole PT relative to CT was equal for the two techniques (Table 3), but the pole ground contact was timed differently within the cycle (Fig. 5). There were no differences in ski PT between weak and strong side for either of the techniques, and the length of overlap between the skis, relative to CT, was also independent of technique.

In the sideways and vertical directions, both hip acceleration and displacement patterns were qualitatively similar in V1 and V2, even if there were some consistent differences. However, in the AP direction distinct differences were found both for acceleration and displacement (Figs 5 and 6). The main differences were (a) the forward acceleration (positive AP acceleration) was closely linked to the pole push in V2, whereas maximal forward acceleration in V1 occurred without pole ground contact; (b) the hip elevated or stayed more or less constant during the poling stroke in V1, whereas in V2 the hip clearly dropped for all subjects; and (c) the patterns of AP hip acceleration and displacement on weak and strong sides were different in V1 while they were similar in V2.

Peak hip acceleration sideways were smaller, whereas peak forward acceleration amplitudes were larger in V2 compared with V1. No differences in peak vertical acceleration between techniques were detected. However, partly because of the longer CT, ranges of displacement were larger in V2 than in V1 in all three directions (Table 2). The total distance the hip moved around the average position on the treadmill was 0.78 (0.11) and 1.16 (0.14) m per cycle for V1 and V2, respectively. The extra distance the hip moved, as a percentage of the linear distance along the treadmill (CL), was 18.8% (1.7%) and 19.9% (1.6%) for V1 and V2, respectively ($P < 0.01$).

Discussion

With use of accelerometers, we have confirmed earlier studies on differences between the two major ski skating techniques, V1 and V2, concerning timing of ski and pole actions. The present study adds to previous studies by showing that with the use of one triaxial accelerometer positioned at the hip, the different skiing techniques can be distinguished from each other during treadmill roller skiing. The data reveal that one of the main

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[4] "Inner pole": left pole when standing on right ski and right pole when standing on left ski.

[5] "Outer pole": opposite to inner pole.

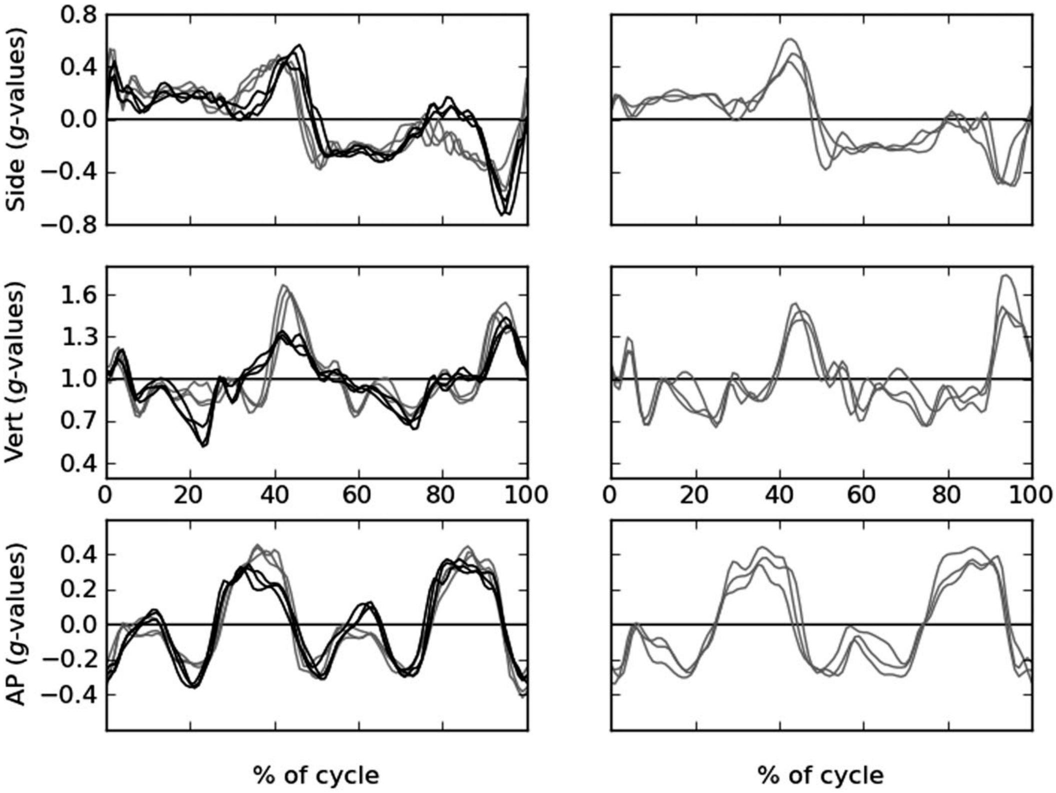

Fig. 4. Left: Between-subject (black vs gray) comparisons of mean hip acceleration curves from two runs in June and one run in October. Different subjects are compared in the different directions (Side, sideways; AP, antero-posterior; and Vert, vertical). Right: A skier with large variation between runs in respective direction.

Table 2. Maximum (max) and minimum (min) acceleration, range of displacement, and the distance the hip traveled during one cycle (Accumulated distance) in V1 and V2. Effect size (ES) between techniques and test-retest correlation and typical error between two trials on the same day in V2

		V1	V2	ES	Sign	Test-retest Pearson *r*	Typical error V2
Sideways acceleration (*g*)	Max	0.62 (0.07)	0.54 (0.08)	1.0	**	0.38	±0.06
	Min	−0.68 (0.12)	−0.61 (0.11)	0.6	$P < 0.1$	0.78	±0.05
Vertical acceleration (*g*)	Max	1.42 (0.11)	1.45 (0.11)			0.81	±0.05
	Min	0.64 (0.10)	0.65 (0.09)			0.85	±0.03
Antero-posterior acceleration (*g*)	Max	0.36 (0.08)	0.41 (0.05)	0.9	$P < 0.02$	0.82	±0.03
	Min	−0.40 (0.06)	−0.35 (0.06)	0.8	**	0.94	±0.02
Resultant acceleration (*g*)	Max	0.83 (0.12)	0.77 (0.12)			0.66	±0.07
	Min	0.20 (0.04)	0.16 (0.04)	1.1	**	0.54	±0.03
	Mean	0.40 (0.03)	0.39 (0.03)			0.74	±0.01
Range of displacement (m)	Side	0.32 (0.05)	0.42 (0.08)	1.5	**	0.82	±0.03
	Vert	0.08 (0.02)	0.12 (0.02)	2.3	**	0.55	±0.01
	AP	0.10 (0.03)	0.15 (0.03)	1.7	**	0.80	±0.02
Accumulated distance (m)	Side	0.64 (0.11)	0.84 (0.15)	1.5	**	0.82	±0.07
	Vert	0.26 (0.05)	0.43 (0.05)	3.5	**	0.62	±0.04
	AP	0.21 (0.06)	0.44 (0.06)	4.1	**	0.80	±0.03
	Total	0.78 (0.11)	1.16 (0.14)	3.1	**	0.73	±0.07

Values are mean (standard deviation).

**$P < 0.01$ between techniques.

AP, antero-posterior; Side, sideways; Vert, vertical.

Table 3. V1 and V2 cycle length (CL), cycle rate (CR), cycle time (CT), push time (PT), recovery time (RT), PT/CT, and pole synchrony (negative value meaning left pole after right pole)

	V1	V2	ES	Sign
CR (Hz)	0.72 (0.04)	0.52 (0.04)	5.3	**
CL (m)	4.16 (0.24)	5.82 (0.42)	5.0	**
Pole CR (Hz)	0.72 (0.04)	1.04 (0.07)	5.5	**
Pole CT (ms)	1383 (79)	969 (69)	5.6	**
Right pole PT (ms)	555 (36)	376 (26)	5.7	**
Left pole PT (ms)	508 (34)	370 (32)	4.1	** #
Right pole RT (ms)	830 (56)	592 (49)	4.5	**
Left pole RT (ms)	873 (73)	599 (52)	4.4	** #
PT/CT	0.384 (0.015)	0.385 (0.018)		
Pole synchrony (ms)				
Plant strong side	0 (16)	−3 (13)		
Plant weak side		−3 (14)		
Liftoff strong side	47 (49)	−5 (10)		** \$
Liftoff weak side		10 (17)		\$

Values are mean (standard deviation).

$^{**}P < 0.01$ between techniques,

$^{\#}P < 0.01$ between poles in V1,

$^{\$}P < 0.01$ between sides in V2.

ES, effect size between techniques.

differences between the techniques is that the hip and center of mass drop during the poling stroke in V2, but not in V1. This allows the potential energy gained by extension of the hip and knee joints in V2 to be transferred through the arms and poles to kinetic energy in the forward direction. Furthermore, despite well-defined features in the different techniques, pattern of locomotion as measured by the hip accelerometer differs significantly between elite skiers but they reproduce their individual patterns between cycles, between runs on the same day, and after 4 months of training. This shows that accelerometers can be a useful tool not only for research in cyclic sports such as XC skiing, but may also give important individual feedback to the skier about her or his individual technique, both post-performance and continuously during the performance of the activity.

Methodological opportunities and limitations

Accelerometers are less accurate than a system including fixed infrared cameras, goniometers, and force measurements in the study of detailed body segment kinematics. However, a significant advantage is that accelerometers

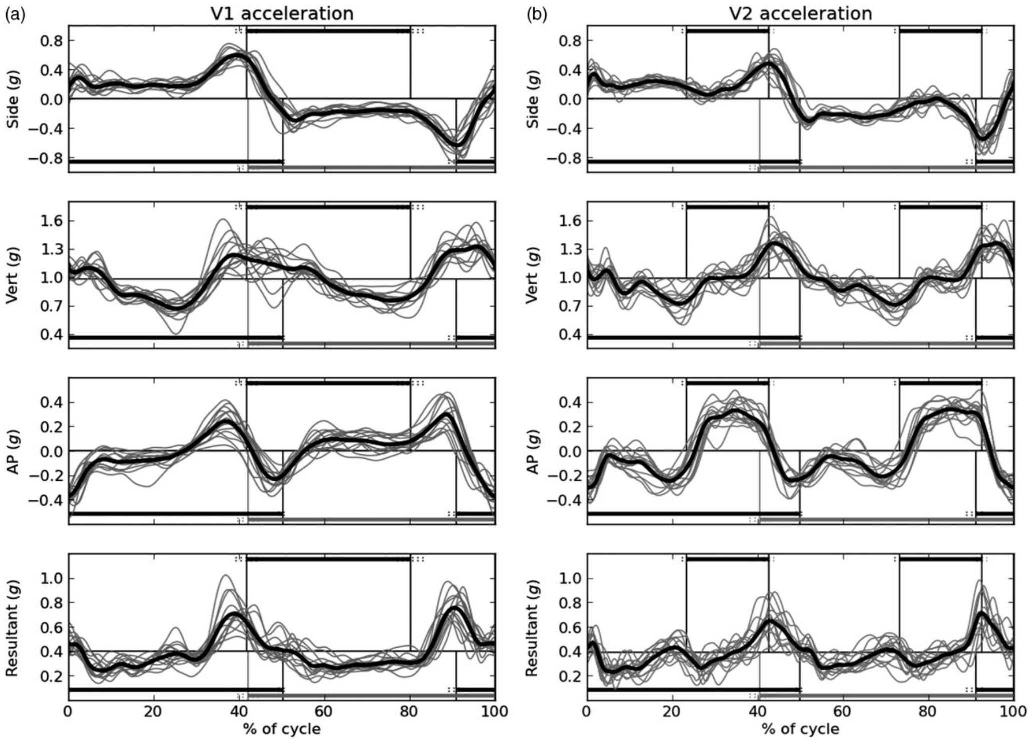

Fig. 5. Sideways (Side), vertical (Vert), antero-posterior (AP), and resultant acceleration of the hip normalized for one cycle for V1 (a) and V2 (b). Each line represents one subject. The black line is the average of all subjects. Black horizontal bars in the upper half of each panel show timing of mean pole contact. Black and gray bars in the lower half of each panel represent weak and strong ski, respectively. Horizontal black line shows mean acceleration over the cycle.

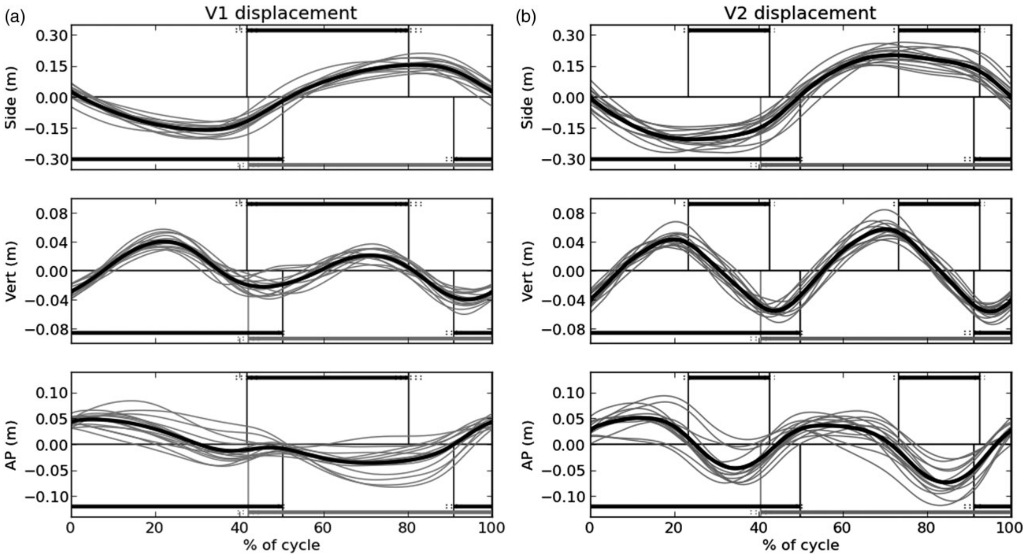

Fig. 6. Sideways (Side), vertical (Vert), and antero-posterior (AP) displacement of the hip normalized for one cycle for V1 (a) and V2 (b). Each line represents one subject. The black line is the average of all subjects. Black horizontal bars in the upper half of each panel show timing of mean pole contact. Black and gray bars in the lower half of each panel represent weak and strong ski, respectively. Horizontal black line shows mean position over the cycle.

are not restricted to a research laboratory environment, are light, and can be carried by the skiers without interfering with their technique and performance. Furthermore, accelerometers do not need any external equipment outside the skier and can therefore be used to collect data during the whole course, for instance during a competition. The accelerometers are easy to use, the data processing is straightforward, and the results are relatively easy to interpret as opposed to information about multiple segment kinetics and kinematics. Furthermore, timing of segments may change with terrain and snow conditions to obtain an ideal movement of the center of mass, and this optimum may change less between conditions than body segment kinematics. The complexity of ski skating involves cyclic movement with acceleration of the center of mass sideways as well as horizontally and vertically. It has been indicated that coordination and timing of the force application is as important as the magnitude of the forces that discriminate skiers of different levels (Stöggl et al., 2010). Hence, study of the center of mass movement and especially the timing of the movement may be as important as detailed body segment kinematics. Our placement of the hip accelerometer (S1) was chosen because it is close to the center of mass in an upright position. But the displacement pattern of the center of mass will differ from the S1 displacement pattern due to arm, leg, and trunk movements within a cycle. Even so, the two-dimensional video analysis revealed similar patterns between vertical movement of center of mass and the hip accelerometer during pole push in both techniques. When flexing the knee while standing, one needs to compensate with either ankle dorsal flexion or hip flexion to keep balance. If hip flexion is chosen, the hip will move both in vertical and in posterior direction. Video analysis of the movement pattern of the hip accelerometer showed that the hip AP movement differs from center of mass during V2 pole push mainly due to hip flexion. During V1 pole push, however, the movement patterns for hip and center of mass AP motion were similar. Asymmetry between poles is well known in V1 (e.g., Smith et al., 1988, 1989; Nilsson et al., 2004) but has not been reported in V2 before. The small asymmetry in V2 in the present study, together with the video validation of pole and ski hits and liftoffs, showed high precision in our temporal pattern method, but the small asymmetry in V2 might also indicate some yaw rotation (rotation around the global z-axes). In our procedure, we used average tilt angles over several cycles to translate acceleration into an approximately global coordinate system and assumed no rotation of the hip. One accelerometer alone cannot measure rotations, and two-dimensional video analysis cannot quantify errors due to lack of rotation measurements. Even though average tilt angle methods have been used in gait analysis (Moe-Nilssen, 1998a, b), assuming no rotation during a cyclic movement like roller skiing is of course a simplification. In other words, the local accelerations will only predict the global accelerations, but because the intraindividual variation is less than the interindividual variation and the two-dimensional analysis confirmed our main finding of larger vertical hip drop in V2 during pole thrusts, we are confident that the method is suitable for detecting key differences between techniques.

Differences between V1 and V2

As V2 by definition has two pole pushes while V1 has only one pole push for every cycle, the most obvious difference between V1 and V2 is the different relative timing of the poles. The present data, which were automatically derived from the data collected from accelerometers on the poles and the skis, confirmed earlier findings of lower CR and longer CL in V2 compared with V1 (Nilsson et al., 2004; Smith et al., 2009). The method also enabled us to detect a longer PT on the strong than on the weak pole during V1, also found by others (Smith et al., 1989; Millet et al., 1998a; Stöggl et al., 2010), due to asynchronous pole liftoffs and synchronous pole plants. In contrast, PT was slightly longer on the weak pole (inner pole) in V2 due to delayed liftoffs. The data from the ski and pole accelerometers also showed that in V1, the pole stroke started synchronized [−5 (60) ms] with the ski stroke on the strong side and ended after 66% (6%) of the ski stroke. In V2, the strong side pole stroke started 55% (3%) into the ski stroke (Fig. 5) and ended after 88% (2%).

Hip speed and displacement were estimated by integration of the acceleration signal. Video analysis revealed that displacement of the hip in the vertical direction approximates displacement of the center of mass and therefore approximates the changes in the skier's potential energy. An important difference between V1 and V2 is the timing of hip vertical displacement in relation to the double-poling action. During V2, the hip is at the highest position just before pole plant and lowered during the poling thrust, with the highest speed in the middle of the stroke when the forward hip acceleration is largest. Hence, the potential energy gained by the extension of hip and knee joints in the first half of the ski thrust is transferred into forward kinetic energy of the skier in the second half simultaneously with the poling action. During V1, there is only minor vertical displacement of the hip during the poling thrust. Interestingly, despite different use of potential energy in V1 and V2, the oxygen cost was the same in the two techniques (Losnegard et al., 2012). However, poling time decreases with higher speeds (Millet et al., 1998a) and there could be a link between the use of potential energy and the fact that V2 is considered being a high-speed technique.

From video analysis it could be established that during the poling action in V2, only minor changes occurred in the angles of the shoulder and the elbow joints during the first ~60% of the poling action, while the angles of the hip and knee joints were decreasing (data not shown). Hence, the shoulder and elbow muscle are working more or less isometrically during the part of the pole thrust with the highest forward acceleration, while the poling action is actively performed by knee and hip flexion. Smith et al. (2009) showed that in V2, more of the propulsive forces came from the poling action than in V1, and furthermore, the poling thrust contributed more to propulsion than the ski thrust. The present data showed that the poling thrust in V2 was accomplished to a large extent by the legs and trunk by first elevating the center of mass to gain a high starting position that enabled a large range of motion, then lowering the center of mass by gravity and active flexion in the hip and knees. The full V2 cycle can be divided into two equal ski strokes, which again can be divided into two functional phases. The first phase starts with the ski set down, which is performed with the hip in the lowest position and the hip and knee joints close to maximally flexed. During phase 1, the hip is elevated by an extension of ankle, hip, and knee joints. Phase 2 includes the pole thrust where the hip is lowered by gravity and active flexion of ankle, knee, and hip joints, followed by the ski stroke where the ankle, knee, and hip joints are extended with an abducted hip (Stöggl et al., 2008). The actions of the elbow, shoulder, knee, and hip joints during pole thrust are very similar to the action during double poling described by Holmberg et al. (2005). However, obviously leg work is different, alternating between left and right ski gliding and with the ski angled to the forward direction. This means that a component of the ski reaction force, which are oriented approximately perpendicular to the ski surface (Smith 2002), will add to the forward propulsion. However, a larger component of the ski reaction force will promote propulsion in the direction of the opposite ski. Due to this component, the net speed of the skier will be directed approximately in the ski direction at the onset of the ski thrust and this speed will be higher than the forward speed (relative to the treadmill belt). Hence, the kinetic energy in the direction of the ski at onset of the ski thrust is higher than in double poling at the same speed. From the speed curves (Fig. 7), it can be seen that the speed sideways and in forward direction in V2 both are at maximum approximately at the start of the ski thrust. However, after the pole thrust the situation in double poling and V2 skate are similar with no (double poling) or very little (V2) forward propulsion from either skis or poles and the speed drops (Fig. 7).

A full cycle in V1 also consists of two leg thrusts, but these are not symmetric. On the strong side, the ski and poling thrust started simultaneously and the poling thrust ended ~66% into the ski thrust. Maximum elevation of the hip on the strong side, 4.8 (1.5) cm, was reached during the poling thrust. On the weak side, there is no poling thrust and the hip was elevated on average 8.1 (1.8) cm, ($P < 0.01$ compared with the strong side). During V2 the elevation of the hip was 11.6 (1.5) cm and 10.6 (1.6) cm on the strong and weak side, respectively, and the elevation occurred before the pole thrust. The pattern of vertical movement (displacement) of the hip timed to the ski thrust was very similar between the techniques (mid panel Fig. 6). The differences between

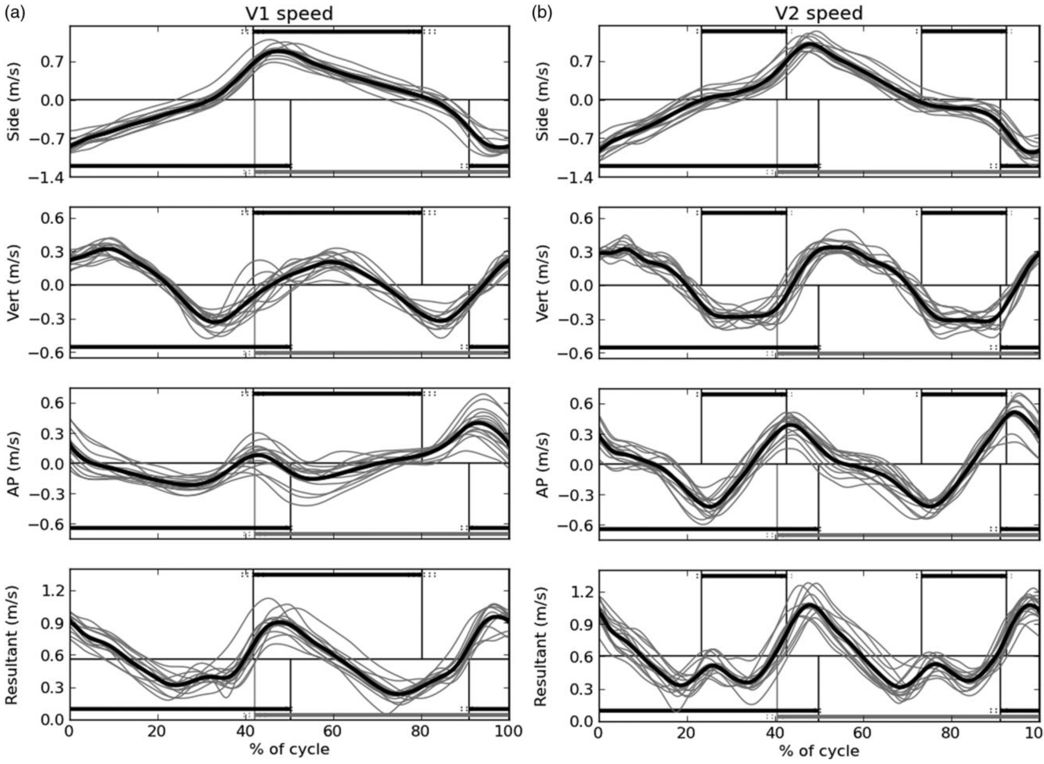

Fig. 7. Sideways (Side), vertical (Vert), antero-posterior (AP), and resultant speed of the hip normalized for one cycle for V1 (a) and V2 (b). Each line represents one subject. The black line is the average of all subjects. Black horizontal bars in the upper half of each panel show timing of mean pole contact. Black and gray bars in the lower half of each panel represent weak and strong ski, respectively. Horizontal black line shows mean speed over the cycle.

the techniques concerning the use of potential energy during the poling thrust are related to the fact that in V1, the poling thrust starts with the ski thrust, while during V2 the poling thrust is during the last half of the ski thrust.

V1 and V2 techniques in XC skiing are characterized by well-defined hip acceleration pattern in the three orthogonal directions. The most important difference is that the hip clearly drops during the poling thrust in V2, but not in V1. Similar to double poling, this allows potential energy gained by extension of the hip and knee joints prior to the poling stroke to be transferred to propulsion through the arms and poles in V2, but not in V1. Further, elite skiers reproduce their individual movement pattern and therefore accelerometers can be used for detailed biomechanical testing of the individual skier as well as in the study of different techniques in XC skiing under different conditions.

Perspectives

The present study shows that with the use of accelerometers on the poles and boots, cyclic characteristics can automatically be collected with high accuracy. In addition, this system can also be used to find technique transitions automatically (Myklebust et al., 2011). The present study adds to that of Marsland et al. (2012) by controlling speed and inclination and using less smoothed signals to establish distinct and easily detectable differences in hip acceleration between V1 and V2, suggesting that each cycle, as well as technique transitions, may automatically be collected with the use of only one accelerometer placed on the hip. An advantage with the accelerometers is that the same equipment setup can be used in the laboratory environment and in outdoor roller skiing and snow skiing, without interfering with technique and performance. Hence, accelerometers can be used to evaluate the differences between roller skiing and skiing on snow. This method might also be suitable for direct feedback systems during skiing, comparison of different level of skiers, documenting development of technique over time, and also detecting changes in technique as fatigue develops.

Key words: inertial sensors, cyclic movements, reproducibility, cross-country skiing, biomechanics.

Abbreviations: AP, antero-posterior; CL, cycle length; CR, cycle rate; CT, cycle time; pole CR, pole cycle rate; PT, push time or contact time; Res, resultant; RT, recovery time; SD, standard deviation; Side, sideways; Vert, vertically; XC, cross-country.

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Paper II

Myklebust H., Gløersen Ø., Hallén J.

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TECHNICAL NOTE

Validity of Ski Skating Center-of-Mass Displacement Measured by a Single Inertial Measurement Unit

Håvard Myklebust,[1] Øyvind Gløersen,[1,2] and Jostein Hallén[1]
[1]Norwegian School of Sport Sciences; [2]University of Oslo

In regard to simplifying motion analysis and estimating center of mass (COM) in ski skating, this study addressed 3 main questions concerning the use of inertial measurement units (IMU): (1) How accurately can a single IMU estimate displacement of os sacrum (S1) on a person during ski skating? (2) Does incorporating gyroscope and accelerometer data increase accuracy and precision? (3) Moreover, how accurately does S1 determine COM displacement? Six world-class skiers roller-ski skated on a treadmill using 2 different subtechniques. An IMU including accelerometers alone (IMU-A) or in combination with gyroscopes (IMU-G) were mounted on the S1. A reflective marker at S1, and COM calculated from 3D full-body optical analysis, were used to provide reference values. IMU-A provided an accurate and precise estimate of vertical S1 displacement, but IMU-G was required to attain accuracy and precision of < 8 mm (root-mean-squared error and range of displacement deviation) in all directions and with both subtechniques. Further, arm and torso movements affected COM, but not the S1. Hence, S1 displacement was valid for estimating sideways COM displacement, but the systematic amplitude and timing difference between S1 and COM displacement in the anteroposterior and vertical directions inhibits exact calculation of energy fluctuations.

Keywords: accelerometer, gyroscope, cyclic movements, biomechanics, cross-country skiing

Center of mass (COM) displacement has been used in cross-country skiing research for calculating mechanical work,[1–3] evaluating a power balance model,[4] studying energy cost,[3] describing different ski skating subtechniques,[5–7] and to distinguish between level of skiers.[3]

With 3D full-body analysis including several cameras, COM displacement, as well as position, speed, and acceleration of joints, limbs, and equipment, can be calculated accurately.[8,9] However, this method is time consuming, costly, and limited to a small calibrated space.[10] Alternatively, body segment kinematics can be studied using inertial measurement units (IMU). IMUs vary from a single axis accelerometer to a combination of 3D accelerometers, gyroscopes, and magnetometers measuring linear acceleration, angular rate, and magnetic orientation. The sensors have become small, wireless, and available at a low cost. Further, they sample at high frequency and are promising for outdoor and ambulatory monitoring.[10,11]

Systems potentially used in the field by athletes and coaches should be simple, preferably consisting of only a single IMU. During walking, os sacrum (S1) displacement has been found to resemble COM displacement rather closely (root-mean-squared error < 8 mm).[12] However, pelvic rotations and movements of the extremities decrease the accuracy of the method.[8,12,13] Ski skating is a complex cyclic movement with extensive hip rotations and use of the upper body.[14] Therefore, the use of 1 single marker is especially challenging for analysis of COM during ski skating.

To develop a mobile system for real-time feedback,[15] the benefit of incorporating more sensors (ie, accelerometers alone[14,16] or in combination with gyroscopes[17]) must be weighed against increased computations. Hence, in an attempt to simplify COM estimation in ski skating, the main questions of this study are: How accurately can a single IMU estimate displacements of S1 on a person during ski skating? Does incorporating gyroscope and accelerometer data increase accuracy and precision? Moreover, how accurately does S1 determine COM displacement?

Methods

Six male cross-country skiers gave their written consent before roller skiing on a treadmill surrounded by a 9-camera optical motion system (see Table 1 and Figure 1 for subjects and equipment details). An IMU including accelerometers, gyroscopes, battery, and Bluetooth radio (IMU-G) was adhered directly at the S1 by medical tape. Another IMU, including a 3D accelerometer but no gyroscope (IMU-A)[14] was adhered to IMU-G. In addition, an accelerometer was attached to the pole grip for pole-plant detection. The S1 reflective marker was placed at IMU-A. After ≈ 30 minutes of submaximal skating, data of the V1 and V2 techniques (Figure 1) were collected at a constant submaximal load ($3.0\ \mathrm{m \cdot s^{-1}}$ and 4°, $\mathrm{VO_{2\text{-}demand}}$: ≈ $48\ \mathrm{mL \cdot kg^{-1} \cdot min^{-1}}$).

Data were postprocessed using Matlab R2012b (MathWorks Inc., Natick, MA). The method of Lai et al[18] was used to convert accelerometer signals to *g*-units. For gyroscope data, the manufacturer's default scaling factors were used, while offset values were calculated from a static measurement the day of testing. A second-order Butterworth low-pass recursive digital filter was applied to both marker and IMU data (cut-off frequencies of 10 HZ and 30 Hz, respectively). The cut-off frequencies were selected based on residual analysis of the different types of signals.

Håvard Myklebust, Øyvind Gløersen, and Jostein Hallén are with the Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway. Øyvind Gløersen is also with the Department of Physics, University of Oslo, Oslo, Norway. Address author correspondence to Håvard Myklebust at havard.myklebust@nih.no.

Table 1 Extended details of subjects, equipment, and analyzed loads

Equipment/ Subjects	Manufacturer/Other Details	Model	Dimension	Software	Sampling Rate	Range	Weight
Treadmill	Rodby, Sodertalje, Sweden		3 m × 4.5 m				
Poles	Skier's personal poles		90% ± 1% of body height				
Roller skis	Swenor, Sarpsborg, Norway Rottefella, Klokkarstua, Norway	Skate, $\mu = 0.016$, NNN bindings	57 cm				870 grams each
Optical system	Qualisys AB, Gothenburg, Sweden	Oqus 400	Diameter marker: 20 mm	Qualisys Track Manager	250 Hz		
IMU-A	PLUX wireless biosignals S.A., Lisbon, Portugal	researchPLUX, xyzPLUX accelerometers	10 mm × 20 mm × 5 mm	loggerPLUX 2.0	1000 Hz	± 3 g	11 grams*
IMU-G	Apertus AS, Asker, Norway	Prototype	55 mm × 38 mm × 10 mm	Custom-made smartphone logger application	101.2 Hz	± 2 g 250 °/s	25 grams
Subjects	Age: 26 ± 2 years, height: 181 ± 5 cm, weight: 79.5 ± 5.3 kg, VO_{2max}: 74.6 ± 5.2 $mL \cdot kg^{-1} \cdot min^{-1}$ Top ten rankings in Norwegian Championships						

Note. * Weight for the 3D accelerometer. Weight and dimension for the researchPLUX data acquisition system was 85 grams and 84 mm × 53 mm × 18 mm.

Data from the different systems were time-synchronized using unbiased cross-correlation[19] of each system's acceleration vector norm. For this purpose, a piecewise cubic spline interpolation of signals was used to get equal sample frequency. In addition, S1 marker data were differentiated twice in each direction, and 1.0 *g* was added to the vertical direction before calculating the acceleration vector norm. After calculating the time shift by cross-correlation, all signals were resampled to 100 Hz.

A full cycle (100%) was defined as the period between 2 strong-side pole-plants (Figure 1) and automatically derived from pole accelerations with accuracy < 0.01 seconds.[14] To compare movement patterns between skiers and subtechniques, 15 time-normalized subsequent cycles were averaged. When the skier stood in a neutral position, the IMUs' local axes (xyz) were approximately aligned with the laboratory reference frame (XYZ, defined as shown in Figure 1). The 2 methods validated (IMU-A and IMU-G) differ in the way they correct for misalignment between the xyz and XYZ reference frames during the cycles. Both methods use the inclinometer properties of accelerometers[20] and, because of the cyclic movement and constant speed, assume average horizontal acceleration vector over the collection period to be zero. The IMU-A method is described by Myklebust et al[14] and it uses the numerical Newton–Raphson method to align the xy and XY planes through a series of coordinate transforms. However, this method neglects intracycle rotations that are obviously present while ski skating. Such rotations cause dynamic misalignments between xyz and XYZ, consequently adding a fluctuating component of gravity to all 3 axes.

The IMU-G method adjusts for such intracycle rotations by calculating S1 linear acceleration in a laboratory-fixed reference frame (XYZ') using the angular rates measured by the gyroscopes, and the strap-down inertial navigation algorithm described by Titterton and Weston.[21] To reduce drift in the orientation estimates due to offset errors in gyroscope output, the linear trend line over the analyzed time period was subtracted from the Euler angles. Finally, the XY'-plane was aligned with the horizontal XY-plane by first cancelling forward tilt angle, and then lateral tilt angle.[20] This procedure ensured that the reference frames of the gyro-stabilized IMU and the laboratory (XYZ) would be identical, under the assumption that the time average of the IMU's x-axis was parallel to the laboratory XZ-plane.

Skiers' COM was calculated based on a 19-segments (hands, lower arms, upper arms, head, torso, pelvis, thighs, legs, feet including boots, poles, and skis) model derived from Visual 3D models (C-Motion Inc., Germantown, MD) and subjects' individual anthropometric data, including height, weight, leg length, and circumference of extremities (Figure 1). In Visual 3D, S1 marker data were adjusted for the location difference between IMU-G and the S1 marker's center. The S1 and COM data derived from Visual 3D were used as reference values. To get IMU displacement estimates comparable with S1 data, a cumulative trapezoidal numerical integration was applied twice for the corrected IMU signals. For both the S1 data and for each integration step of the IMU data, the mean was subtracted from the data, since speed was constant.

Validity was evaluated along each of the 3 orthogonal laboratory axes. Root-mean-squared (RMS) error quantifies overall deviation between estimate and reference values for a full cycle. Range-of-displacement and timing-of-peak-amplitude (timing) deviations quantify whether the differences are caused mainly by amplitude (difference between maximum and minimum amplitude) or timing errors, respectively. All data are presented as group means ± standard deviation. The group mean difference represents accuracy and the standard deviation represents the precision of the estimate.

Results

The IMU-G method estimated S1 displacement with RMS error < 8 mm in all directions in both subtechniques (Table 2). The errors were due to differences in both range of displacement and timing (Table 2 and Figure 2).

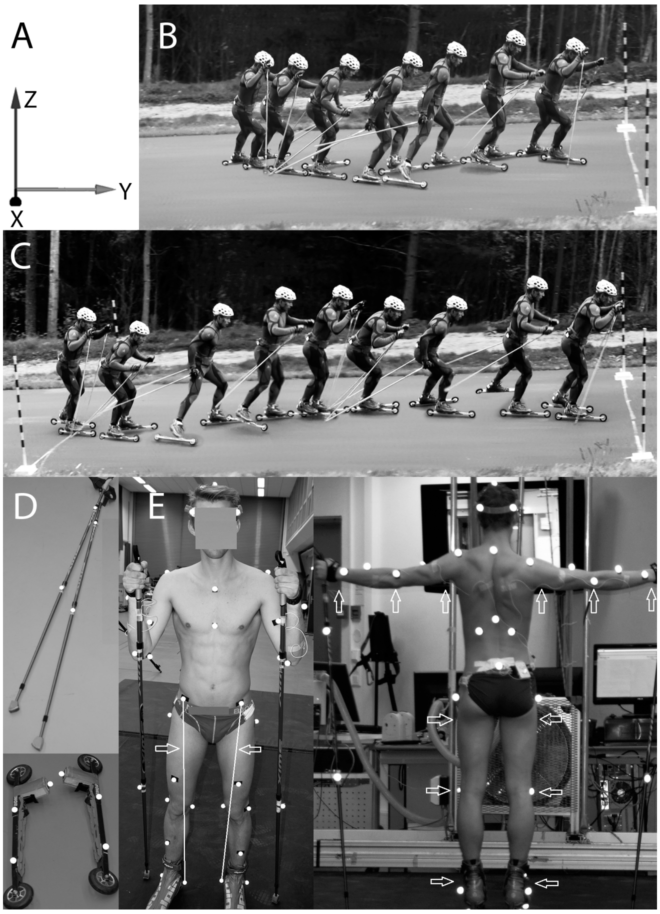

Figure 1 — (A) Reference coordinate frame (XYZ) was defined from weak to strong side (X), forward (Y), and upward (Z), with XY as the horizontal plane. (B) V1 is generally considered to be an uphill technique characterized by asymmetrical use of the upper body in one asynchronous double-poling action per cycle, timed with one of the skating strokes (strong side). (C) In contrast, the V2 technique is symmetrical in that there is one synchronous double-poling action within each skating stroke. (D) The athletes used poles modified with a customized tip for the treadmill and the same pair of skate roller skis. (E) Body weight, height, and leg length and circumference of the extremities (arrows) were used for center of mass calculations. A total of 44 reflective markers were placed on body landmarks and equipment.

Table 2 Differences between IMU methods and reference values (the reflective marker at S1) in the laboratory reference frame, group mean ± standard deviation

		ROD Deviation (mm)			TPA Deviation (% of cycle)			RMS Error (mm)		
Technique	**Method**	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
V1	IMU-A	12 ± 31	–19 ± 23	6 ± 9	–5 ± 1	–5 ± 3	–1 ± 0	32 ± 7	24 ± 8	6 ± 1
	IMU-G	1 ± 10	–1 ± 5	–1 ± 1	0 ± 1	1 ± 4	0 ± 0	4 ± 2	7 ± 6	1 ± 1
V2	IMU-A	3 ± 51	–36 ± 15	1 ± 5	–13 ± 6	0 ± 6	–2 ± 1	69 ± 14	23 ± 7	10 ± 2
	IMU-G	–6 ± 13	–7 ± 5	1 ± 1	0 ± 0	3 ± 2	0 ± 0	5 ± 3	7 ± 2	1 ± 0

Abbreviations: IMU = inertial measurement unit; IMU-A = IMU including accelerometers alone; IMU-G = IMU combining accelerometer and gyroscope data; ROD = range of displacement; TPA = timing of peak amplitude; RMS = root-mean-squared.

Correcting for intracycle rotations (IMU-G) increased accuracy and precision of S1 estimates, both in terms of timing and range of displacement (Table 2, Figure 2, and Figure 3). Compared with the IMU-A method, the IMU-G method reduced average vertical RMS error from < 11% to < 2% of S1 range of displacement for both subtechniques (Table 2 and Table 3).

Displacement of S1 and COM was in best agreement in the sideways direction with RMS error of approximately 5% of COM range of displacement (Table 3 and Figure 4). The differences were substantially larger (RMS error up to 72% of COM range of displacement) in the anteroposterior and vertical directions, with differences in both range of displacement and timing (Table 3 and Figure 4).

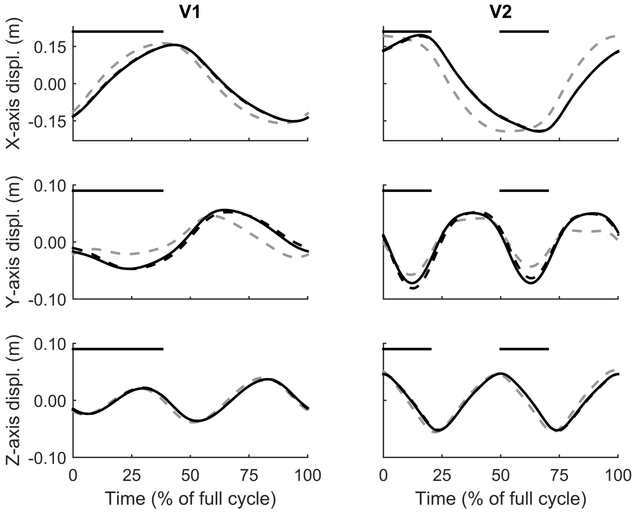

Figure 2 — In comparison with the S1 reference (solid black line), the IMU-A method (gray dashed line) resulted in larger errors than the IMU-G method (black dashed line). The curves show the group average displacement (displ.), and the horizontal black lines indicate the timing of pole push.

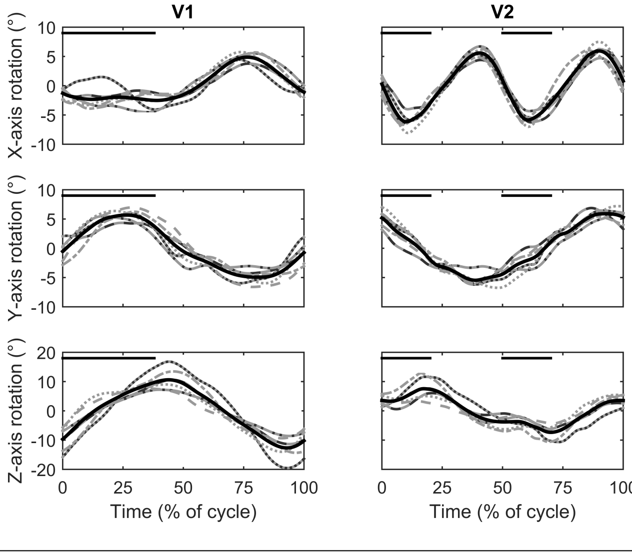

Figure 3 — Individual hip rotation angles during V1 (left) and V2 (right). Angles are in the laboratory reference frame (XYZ), calculated from pelvis markers. The black curves are the group average curves. The horizontal black lines indicate the timing of pole push. For comparison reasons, Y-axis and Z-axis rotation curves were flipped for skiers using the left as the strong side in V1.

Table 3 Center of mass (COM) and os sacrum (S1) comparison in the laboratory reference frame, group mean ± standard deviation

		ROD (mm)			TPA Deviation (% of cycle)			RMS Error (mm)		
Technique	**Location**	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
V1	COM	281 ± 23	49 ± 10	108 ± 18						
	S1	313 ± 38	104 ± 15	79 ± 21	1 ± 1	0 ± 4	–1 ± 1	15 ± 5	21 ± 4	21 ± 2
V2	COM	394 ± 35	46 ± 7	132 ± 11						
	S1	390 ± 50	124 ± 7	101 ± 21	1 ± 1	5 ± 2	3 ± 1	16 ± 5	32 ± 4	23 ± 1

Abbreviations: ROD = range of displacement; TPA = timing of peak amplitude; RMS = root-mean-squared.

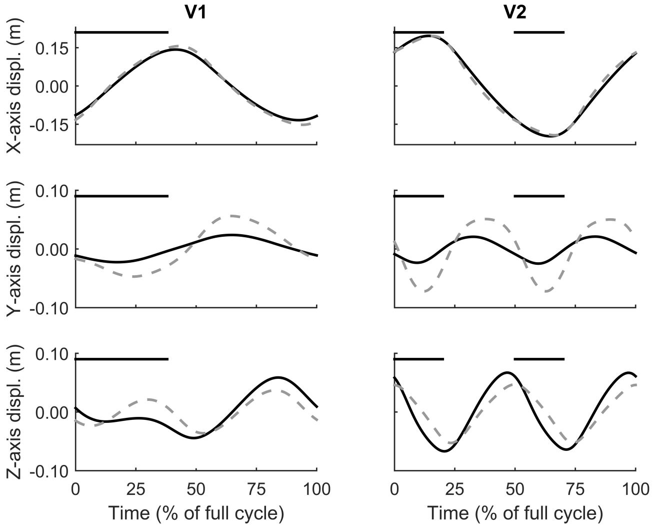

Figure 4 — Time-normalized group average displacement (displ.) curves in the laboratory reference frame (XYZ) for center of mass (black lines) and the marker at S1 (gray dashed lines). The horizontal black lines indicate the timing of pole push.

Discussion

The main questions of this validation study were: How accurately can a single IMU estimate displacements of S1 on a person during ski skating? Does incorporating gyroscope and accelerometer data increase accuracy and precision? And, how accurately does S1 determine COM displacement? The major finding was that errors in S1 displacement estimates were a few millimeters in all directions and both subtechniques when combining 3D accelerometer and gyroscope data. Further, sideways COM displacement was accurately estimated by S1 displacement, but there were large systematic deviations in the vertical and anteroposterior directions.

The method presented requires constant external conditions. The external load was chosen since both subtechniques are used at this intensity, and because comparison between different level of skiers is possible at this load.[22] If different external loads affect upper body movements, it might influence the precision of estimating COM by an IMU at S1.

Analyzing acceleration data are sufficient for valid temporal pattern characteristics of ski skating[14] and classification of subtechniques.[15] However, the current study showed that including gyroscopes to correct for the relatively small (< 20°) and consistent intracycle rotations is necessary for accurate and precise estimation of displacement. The IMU-G method almost entirely removed timing errors and strongly increased precision in range-of-displacement estimates for all directions (Table 2 and Figure 2). The RMS error of IMU-G was < 8 mm in all directions, while such small errors were only found in the vertical direction for IMU-A. Further, both methods showed better accuracy and precision in the vertical direction than in the horizontal directions (Table 2). This shows that small misalignments with the gravity vector affect the xy-plane more than the vertical direction and can be explained by the way gravity affects accelerometers (sine vs cosine to the misalignment angle).

The IMU was positioned at S1 because S1 has been used in gait analysis,[12,19,20,23] and because cross-country skiing coaches focus on the hips' movements. For evaluating differences between subtechniques, external conditions, or individual technique, method sensitivity is important. However, accurate and precise estimation of COM displacement is essential to make inferences about energy fluctuations[2] and understanding the effects of ground forces acting on the skier.[7] One research question was therefore what S1 displacement can tell about COM displacement. The current study showed large individual differences in COM range of displacement, but only small variations in RMS error between S1 and COM displacement (Table 3). This indicates high method sensitivity and that the differences in S1 and COM displacement are highly systematic.

For both subtechniques tested, displacement of S1 and COM was in best agreement in the sideways direction. There was no clear difference in S1 and COM range of displacement for the V2 technique (Table 3 and Figure 4), and S1 sideways range of displacement was slightly (≈11%) larger than COM range of displacement in the V1 technique. According to the measured rotations and practical experience, this difference in V1 was caused by the combination of the posterior position of S1 compared with COM and that skiers rotate their torso toward the middle of the treadmill during the pole push (Figure 3 and Figure 4). As previously shown by 2D video analysis in V2,[14] the largest relative deviation from COM range of displacement occurred in the anteroposterior direction (Table 3). In V1, the vertical COM dynamics are highly asymmetric between the 2 sides, while vertical S1 dynamics are more symmetric (Figure 4). This is mainly because of sagittal arm and torso movements, since hip flexion and pole push are executed on one side, and repositioning of the arms and torso (hip extension) is executed on the other side (Figure 1B). This will cause COM to elevate less and more than S1 respectively (Figure 4). In the symmetrical V2 technique, the arms and torso are repositioned for each skating stroke, and vertical S1 displacement is more similar to COM displacement. However, there were systematic differences in both timing and range of displacement (Figure 4 and Table 3). Hence, substantial arm and torso movements limit accurate calculations of energy fluctuation.

In summary, vertical S1 displacement was estimated relatively accurately using a 3D accelerometer. However, correcting for intracycle rotations using gyroscopes was required to attain accuracy and precision < 8 mm (RMS error and range-of-displacement deviation) in all directions. Further, S1 displacement is a valid measure for sideways COM displacement. However, upper body work caused systematic amplitude and timing differences in the anteroposterior and vertical directions, and this inhibits exact calculation of energy fluctuations.

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Paper III

Losnegard T., Myklebust H., Ehrhardt A., Hallén J.

Kinematical analysis of the V2 ski skating technique: a longitudinal study.

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Kinematical analysis of the V2 ski skating technique: a longitudinal study

Authors:

Thomas Losnegard, Håvard Myklebust, Angela Ehrhardt & Jostein Hallén

Institution:

Department of physical performance, Norwegian School of Sport Sciences, Oslo, Norway

Address for correspondence:
Thomas Losnegard, PhD
The Norwegian School of Sport Sciences
Post Box 4014 Ullevål Stadion, 0806 Oslo, Norway
Email: Thomas.losnegard@nih.no
Tlf: +47 22 26 22 73
Fax: +47 22 23 42 20

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Abstract

To characterize timing of movements and evaluate effects of technique alterations in V2 ski skating, thirteen elite male cross-country skiers (age, 23 ± 2 years.; height, 182 ± 6 cm; body mass, 76 ± 8 kg; V2 VO_{2max}, 79.3 ± 4.4 $mL \cdot kg^{-1} \cdot min^{-1}$) were tested four times during the preparation and competition phase on a roller ski treadmill. Each test consisted of submaximal intensities of exercise for determination of oxygen cost followed by one 1000-m performance test. Hip movement (from accelerometer data) and joint angles (2D video) were determined for high-intensity exercise (6° and 3.5 $m \cdot s^{-1}$; ~ 97–100% of VO_{2max}). Each ski thrust was divided into three phases: (I) Gliding phase (18–50% of cycle time); (II) poling phase (50–70% of cycle time); and (III) kick phase (70–78% of cycle time). Flexion/extension of the hip initiated all phases, followed by the respective joints in legs and arms. Mixed-model analysis, adjusting for systematic time effects, identified that both reduced vertical hip acceleration and increased cycle time gave a likely small reduction in oxygen cost and 1000-m time. In conclusion, well-developed hip movement is a key characteristic of the V2 technique for elite-standard skier's long-term performance development.

Introduction

Cross-country skiing consists of two main techniques: classic and skating. The skating technique is a complex cyclic movement with many degrees of freedom. As the mean speed in World-cup races has increased markedly over the last two decades, the V2 technique (poling phase for every ski thrust; also called “Gear 3”) has become the most commonly-used technique in race events (Losnegard, 2013; Stöggl & Müller, 2008). Thus, improvements in the V2 technique are of high priority for competitive skiers.

Several studies have used cycle characteristics to describe the V2 technique and the consensus is that speed is related to cycle length (e.g. Bilodeau, Rundell, Roy, & Boulay, 1996; Losnegard, Myklebust, & Hallén, 2012). However, from a kinematical perspective, only a limited number of studies have investigated why skiers demonstrate this pattern. Sandbakk, Ettema, and Holmberg (2013) compared the V2 technique with and without contribution from the poles at constant speed. They demonstrated that poling reduced the centre-of-mass sideways range of motion, while cycle time and the vertical centre-of-mass range of motion increased. Moreover, a high centre-of-mass position before the poling phase has been suggested as important to increase propulsion for both the V2 and the classic style double poling technique (e.g. Danielsen, Sandbakk, Holmberg, & Ettema, 2015; Myklebust, Losnegard, & Hallén, 2014).

In double poling, the joints are engaged in a sequential pattern (proximal to distal joints) before and during the poling phase (Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller, 2005). Skiers show similar sagittal-plane lowering of centre of mass during the pole thrust in double poling and V2 techniques (Myklebust et al., 2014). Hence, a distinct proximal to distal joint sequence is probably also important in the V2 technique. From a practical point of view, timing of force application is considered to constitute one of the most important characteristics of effective technique and this timing is one of the major discriminating factors between different standards of skier (Stöggl, Müller, Ainegren, & Holmberg, 2011). However, these characteristics are rarely described in the literature.

The overall goal of technique alterations for a competitive athlete is to improve performance. Therefore, the need to evaluate whether its use leads to such improvement is important, but interventions or combined longitudinal and physiological studies are rare in biomechanical analyses (Lees, 2002). Although different standard skiers show different movement patterns and physiological responses at the same skiing speed (Sandbakk, Holmberg, Leirdal, & Ettema, 2010), it is not clear if imitating better skiers’ technique will lead to enhanced performance. Therefore, an alternative approach is to follow the same skiers during a training period. Recently, it has been shown that a single inertial measurement unit (IMU) accurately distinguish different sub-techniques (Marsland et al., 2015; Stöggl et al., 2014) and different skiers during ski-skating (Myklebust et al., 2014). Hence, an IMU should be able to evaluate the effect of skiers' technical alterations on performance.

Using elite-standard skiers, the V2 skating technique and a longitudinal design, the present study investigated whether enhanced performance was related to kinematical alterations, and how IMU-data could contribute to monitoring individuals' technique alterations. We hypothesized that: (I) The V2 technique is characterized by distinct timing sequences where the movement starts with the hip joint and is followed by joints in the legs and arms; (II) hip IMU data can quantify essential technique alterations affecting the work economy and performance of elite skiers.

Methods

Participants.

Thirteen elite male senior cross-country skiers (age, 23 ± 2 years; height 182 ± 6 cm; body mass 76 ± 8 kg) participated in the study. All had regularly participated in rollerski treadmill testing over the previous 2–4 years. Their V2 VO_{2max} (the highest individual VO_{2peak} during the season) was 79.3 ± 4.4 $mL \cdot kg^{-1} \cdot min^{-1}$. Training history for the annual training cycle (12 months) and competition results of the participants has been presented in a previous article (Losnegard, Myklebust, Spencer, & Hallén, 2013). The Regional Ethics Committee of Southern Norway approved the study, and participants gave their written consent before entering the study.

Experimental design.

To characterize timing of movements and evaluate effect of technique alterations, eleven participants performed an identical protocol four times during an annual training year (June, August, October and January). Additionally, two of the eleven skiers were also tested the following June, and two additionally skiers were tested in October and January. Hence, in total 50 tests were included for the accelerometer analyses, whereas 44 tests were included for joint movement’s analyses.

Procedures.

The participants performed 4–6 submaximal bouts of exercise (3.5–6.0°, 3 $m \cdot s^{-1}$), each of 5 min duration with 2 min breaks. The individual oxygen cost (measured between 2.5 and 4.5 minutes at each trial) was calculated as the mean from three bouts (3.5, 4.5 and 5.0°, completed at all tests). Participants then performed a 1000-m time-trial test including assessment of VO_{2peak}. The 1000-m test was performed at 6°. The speed between 0–100 m, up to 200 m, and after 200 m was 3.25 $m \cdot s^{-1}$, 3.50 $m \cdot s^{-1}$, and self-selected, respectively. Video and accelerometer data captured between 100–200 m (6° and 3.5 $m \cdot s^{-1}$) were analysed for all tests. This speed was the greatest that was performed identically at all tests, and corresponded to an oxygen demand of ~74–76 $mL \cdot kg^{-1} \cdot min^{-1}$ and ~97–100% of VO_{2peak}. Changes in physiological responses and performance was reported in Losnegard et al. (2013). Briefly, from June to January 1000-m time (-7.4% ± 1.9% [mean ± 90% confidence limits], effect size = 1.37, $P < 0.05$) and oxygen cost (-3.0% ± 1.2% [mean ± 90% confidence limits], effect size = 0.63, units: $mL \cdot kg^{-1} \cdot min^{-1}$, $P < 0.05$) reduced, whereas VO_{2peak} did not change systematically (1.3% ± 2.4% [mean ± 90% confidence limits], effect size = 0.17, units: $mL \cdot kg^{-1} \cdot min^{-1}$, $P > 0.05$).

Movement capturing.

All tests were performed on a rollerski treadmill (Rodby, Sodertalje, Sweden). The skiers used Swix CT1 poles (Swix, Lillehammer, Norway) and Swenor Skate rollerskis (Swenor, Sarpsborg, Norway) with wheel type 1 ($\mu = 0.020$). Each skier used the same pole length at all tests (165 ± 6 cm, ~91 ± 1% of stature). The skiers wore an IMU system from PLUX Wireless Biosignals S.A. (Lisbon, Portugal). It included one accelerometer at each pole and ski boot for analyzing timing of the pole and ski ground contact hits and liftoffs, and a fifth accelerometer adhered directly to the skin at the os sacrum, vertebra 1 (hip). Data were transmitted via Bluetooth for logging on a computer at 1000 Hz (boot and hip accelerations) and 125 Hz (pole accelerations; sampling rate limited by data acquisition unit). For further details, see Myklebust et al. (2014), as the system and setup was identical. Video was captured at a distance of 6.6 meters perpendicular to the skiing direction (Sony DCR-TRV900E; Sony, Tokyo, Japan).

Accelerometer data analysis.

Data were post-processed using Matlab R2012b (MathWorks Inc., Natick, MA, USA). Timing of limb ground contact was automatically derived from pole and boot accelerometers as described and validated by Myklebust et al. (2014). In the present study, the cycle started (0%) and ended (100%) at the right pole plant during the left ski thrust. Cycle time, poling time, and recovery time, were defined as time between every second right pole plant, a pole plant and subsequent pole liftoff, and from pole liftoff to subsequent pole plant, respectively. Because of technical problems, hip movements from six tests were lost. The following analysing steps, except step 6, were identical to the "IMU-G" method validated by Myklebust, Gløersen, and Hallén (2015):

1. Defining the laboratory reference frame (XYZ) as right-handed, moving along the surface with constant speed, with horizontal XY-plane and anterior direction as positive Y-axis.
2. Conversion to *g*-units using offset and scaling factors.
3. Filtering data using a 30 Hz low-pass second order Butterworth recursive digital filter. The cut-off frequency was selected based on a residual analysis.
4. Applying a rotation matrix to meet the assumption that mean horizontal acceleration is zero at constant speeds.
5. Time-normalizing data to a full cycle automatically derived from pole accelerometers.

6. Adjusting for intra-cycle rotations using the V2-specific rotational pattern presented by Myklebust et al. (2015)
7. Subtracting gravity (1.0 g) from vertical acceleration values before calculating resultant accelerations (vector norm - independent of direction).
8. Applying a cumulative trapezoidal numerical integration twice, to obtain the hip displacement. For each integration step, the mean was subtracted from the data since the speed was controlled and constant.

Since gyro data were not available in the present study, step 6 was included and order of analysing steps slightly changed compared to the IMU-G method validated Myklebust et al. (2015). The same method was applied to all collected data and the error in the vertical range of displacement was expected to be < 2 mm. Presented results are based on individual skiers' mean curve calculated from 10 subsequent time-normalized cycles. Amount of acceleration in the different cycle phases was quantified as root-mean-squared acceleration for each orthogonal direction and the resultant vector norm. In addition to acceleration, curves showing displacement from the corresponding cycle's mean location on the treadmill are presented.

Joint kinematics.

Right side joint angles were calculated from video (25 Hz) using Tracker 4.84 (Douglas Brown, Open Source Physics). The pole tip and six joint centers (wrist, elbow, shoulder, hip, knee and ankle) were manually marked. Then, coordinates for each of 5 subsequent cycles were time-normalized, using a third order 101-point interpolation, before joint angle calculations and averaging the five cycles for further analyses. The participants were analysed one by one in chronologically order. Notice that angles presented are the 2D projection to the sagittal plane through the represented joint (Figure 1). Further, the ankle angle is not the true foot wrist angle, but calculated from the knee and ankle coordinates and the horizontal plane thru the ankle joint (Figure 1). During the right ski thrust, the horizontal distance between the pole tip and the ankle joint at pole plant was defined as forward pole plant.

<<FIG 1 NEAR HERE>>

Statistical Analyses.

All data are presented as mean ± standard deviation if not otherwise stated. The results in June and January are focused to highlight the main changes over the training period. Since measurement error often is a factor (e.g. oxygen cost error is ± 3%), all raw data (except joint angle data) were log-transformed to ensure uniformity of error residuals prior to further analysis. Pearson's Product Moment Correlation with 90% confidence limits was calculated between both raw data and change scores from June to January. Thresholds used for small, moderate, large, very large and extremely large correlation coefficients were 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (Hopkins et al., 2009), and a relation was stated as clear if the confidence limits did not cover both positive and negative relations > 0.1, which means $r \geq \pm 0.4$ for the number of participants tested. Changes were determined using a two-tailed paired t-test, and magnitude of differences was expressed as standardized mean differences (Cohen's *d* effect size). Thresholds for interpreting differences as small, moderate, large and very large effect size were 0.2, 0.6, 1.2, 2.0, respectively (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical calculations were performed with, Microsoft Excel (Redmond, WA) and SigmaPlot 11.0 (San Jose, CA). A level of $P < 0.05$ was considered significant.

To evaluate effects of technique alterations on performance, mixed-model analysis (IBM SPSS Statistics 21) was used to allow for repeated measurements (two to four tests), missing data, individual responses, and adjustment for time-point effects (e.g. because of physiological effects of adjusted training loads etc.). Changes of log-transformed scores from each individual's mean of available tests ensured uniformity and retrieved relative changes. The oxygen cost (units: $mL·min^{-1}$) was a strong mediator for the technical variables' effects on performance. Hence, oxygen cost was used as dependent variable. The model allowed for random effect of participants, and adjusted for time point of testing (June, August, October, January, May) and changes in body mass (including equipment mass). One by one, a technical variable was then included in the model. Relative change slopes (% per % after back-transformation) with ± 90% confidence limits, within-participant variation over the whole season, and model residuals for each variable are presented. A reduced effect of test time point and/or reduced model residual was anticipated for important technical variables. Using magnitude thresholds presented by Hopkins et al. (2009), the smallest worthwhile effect of 1.1-1.4 % of ski racing times found by Spencer, Losnegard, Hallén, and Hopkins (2014), and adjusting for oxygen cost's effect of performance, resulted in magnitude thresholds of 0.5%, 1.6%, 2.8%, and 4.3% of oxygen cost, for small, moderate, large and very large performance effect, respectively. This scale was used for probabilistic description of effects: <0.5%, most unlikely; 0.5%–5%, very unlikely; 5%–25%, unlikely; 25%–75%, possibly; 75%–95%, likely; 95%–99.5%, very likely; 99.5%-100%, most likely (Hopkins et al., 2009).

Results

***Kinematic analyses of the V2 technique*.**

Using limb acceleration data, the right ski thrust (18–78% of cycle time) was divided into three visually distinct phases: (I) Gliding phase (18–50% of cycle time); (II) poling phase (50–70% of cycle time); and (III) kick phase (70–78% of cycle time) (Figure 2). Phase I included an overlap with the left ski kick phase (ending ~28%) and a pure glide phase (28–50% of cycle time). The end of phase II and the whole phase III overlapped with the left ski gliding phase (starting ~67% of cycle time). During the gliding phase (I), the hip was elevated 14 ± 2 cm and this phase was initiated by a peak in vertical acceleration and terminated by a nadir of vertical hip acceleration (Figure 3). The hip elevation was a result of hip, knee and ankle joint extensions starting at ~19%, ~22% and ~29% of cycle time, respectively (Figure 2). The arm movements in this gliding phase involved completion of the previous poling with shoulder and elbow extensions before the arms were moved forward (shoulder flexion) and the elbows were flexed. During poling (phase II), the hip was lowered (Figure 3). Before pole plant, hip-flexion was initiated (~45 % of cycle time), while knee and ankle joint flexions started approximately at pole plant (~49% and ~50% of cycle time, respectively). Shoulder joint extension started slightly after pole plant (~52% of cycle time), while elbow flexion in the gliding phase was continued into the poling phase before elbow extension started at ~57% of cycle time. The kick phase (III) was characterized by a rapid hip, knee and ankle extension. However, the hip and knee joint extensions started during the poling phase (~64% and ~66% of cycle time, respectively), while the ankle joint extension started just after pole liftoff (~72% of cycle time). Ankle and knee joint extensions were terminated at the end of the kick phase, while the hip joint extension continued into the gliding phase of the opposite leg. Thus, the duration of the hip extension was longer than the knee extension, which in turn, was longer than the ankle extension (all $P < 0.05$).

<<FIG 2–3 AND TABLE 1 NEAR HERE>>

Kinematic alterations.

There were no clear correlations between cycle time and 1000-m time, or cycle time and oxygen cost at any test time point. However, cycle time increased from June to January because of increased durations of poling and repositioning (Table 1). The increased poling time was mainly a consequence of more forward pole plant relative to the ankle, and the increased reposition time occurred because of increased pure-glide time (28-50% of cycle time), but not kick time (Table 1). While lateral displacement increased, vertical and anterior-posterior displacements did not change from June to January (Table 1, Figure 3). Further, pure-glide root-mean-squared accelerations (all directions) and full-cycle root-mean-squared accelerations (all except sideways direction) were reduced from June to January (Table 1).

A linear mixed model adjusting for a fixed effect of time point and random effect of participants, distinguished between-participants variation of 9.7% in oxygen cost and an unexplained residual of 5.2%. Change in body mass had a very likely moderate (90% confidence limits: small to large) positive effect on oxygen cost and performance, reduced the residual to 3.9%, and was included when the technical variables were included one by one (Table 2). Changes in poling time (phase II) and vertical root-mean-squared acceleration showed the greatest likelihood (91%

negative and 84% positive, respectively) for a substantial effect on oxygen cost and performance. Figure 4 illustrates the amount of the seasonal decrease in oxygen cost that was explained by alterations in cycle time or vertical acceleration.

<<FIG 4 AND TABLE 2 NEAR HERE>>

In January compared with June, hip angle was less at the start of the gliding phase (I) and the hip joint tended to have greater range of motion during this phase ($P = 0.11$, Fig 2). There were no changes in knee and ankle angle, i.e. the trunk was leaning more forward relative to the horizontal in January than in June ($P < 0.05$). Throughout the poling phase (II), the knee and ankle joint were more extended in January compared to June ($P < 0.05$). In addition, the minimum flexion-angle in the knee joint tended to occur later in January compared to June (~67% vs. 65% of cycle time, $P = 0.07$). At pole plant, elbow extension and shoulder flexion were greater in January than June (both $P < 0.05$). Elbow flexion was coordinated with the pole plant, with an associated increase in range of motion ($P < 0.05$), whereas the subsequent elbow extension range of motion did not change. Furthermore, the maximum flexion in the elbow joint occurred later in the poling phase (~59% vs. 57% of cycle time, $P < 0.05$) and shoulder extension range of motion increased from June to January ($P < 0.05$). Changes in elbow flexion range of motion and shoulder extension were related to changes in cycle time from June to January (r = 0.67 and 0.85, respectively; both $P < 0.05$). Further, changes in elbow flexion range of motion were related to changes in forward pole plant (r = 0.64, $P < 0.05$). During the kick phase (III), hip, knee and ankle range of motions were reduced from June to January (all $P \leq 0.06$). At ski liftoff, the hip and knee joint were less extended in January compared to June ($P < 0.05$).

Discussion

The present study adds to previous work on technique analysis in cross-country skiing by integrating a longitudinal, physiological and biomechanical perspective in a group of elite-standard athletes. The principal findings were: (I) The V2 technique was characterized by distinct sequences of joint movements, starting with the hip and followed by joints in the legs and arms; (II) Both smoother hip movements (reduced root-mean-squared accelerations) and increased cycle time gave a likely small reduction in 1000-m time and oxygen cost.

Kinematic analyses of the V2 technique.

The V2 technique consists of two symmetrical ski thrusts with a double poling action superimposed in the last half of both ski thrusts. We divided each ski thrust into three visually distinct phases. The primary goal of the pure gliding phase (I) is to reposition body segments and elevating centre of mass with a minimum loss of momentum and to provide recovery of propulsive muscles. In the poling phase (II), the hip and upper-body are initially lowered and forward tilted (Figure 2, Figure 3). This prolongs the poling time, and the force impulse, as found in double poling (Lindinger & Holmberg, 2011). In the kick phase (III) the hip extension starts before pole liftoff, followed by knee and ankle extension. Hence, the ski thrust is characterized by a body extension-flexion-extension pattern initiated by the hip, followed by knee and ankle movements. The arms follow the same timing, with shoulder and elbow extension and flexion occurring after the initial movement of the hip. This implies that the timing of the hip movement is fundamental for other joint movements in the V2 technique.

Kinematic alterations.

The hip was more flexed, while the knee and ankle joint were similar at the start of the gliding phase (I) in January compared to June. Thus, the skiers demonstrated a more forward leaning position of the trunk, relative to horizontal, after the training period. During the poling phase (II) the knee and ankle angles were greater in January, while the hip angle was similar. Further, the minimum knee flexion angle tended to occur later in the poling phase in January compared to June. Combined with the possibly small positive effect of kick phase vertical root-mean-squared acceleration on performance (Table 2), this implies that the changed transition between poling and kick phase is an example of more optimal timing application between poles and skis. Such improved timing could potentially lead to a smoother whole-body movement.

The skiers tried to peak their performance for the main events of the season, which were in January. Since physical condition may theoretically alter skiers’ technique in some way, causal relationships between technique parameters and performance cannot be drawn without cautions. However, the mixed model adjusted for the overall changes over time. Since there were still clear relationships between oxygen cost and technical parameters after the adjustment, this strengthen the assumption of causality. Figure 4 illustrates the amount of the seasonal change in oxygen cost and the amount that the technical variables accounted for. Small likely negative and positive effects on oxygen cost were found for cycle time and vertical acceleration, respectively. Hence, a slow smooth movement with low vertical acceleration seems favorable in terms of oxygen cost and performance. An effect of cycle time on performance, or more precisely poling and pure glide time (Table 2), has not previously been shown at an individual level for the V2 technique. Leirdal, Sandbakk, and Ettema (2011) used a cross-over design, but did not find any effect on oxygen cost by acutely altering frequency (cycle time). It is plausible that longitudinal adaptations are more functional and have different effects compared to acute forced alterations in technique.

The definition of acceleration (change in velocity / time) shows that there is a link between acceleration and time, and time to perform a non-linear movement will directly affect the amount of acceleration. Additionally, the acceleration measured by an IMU reflects the resultant of force impulses affecting the IMU. The force impulses result from muscle contractions, which have a metabolic cost. Hence, a positive relationship between change in oxygen cost and change in hip acceleration is logical. Further, if the hip displacement is identical, metabolic cost and time will be negatively related. This is in line with the findings of Zoppirolli et al. (2015), who found longer double-poling cycle-time and reduced vertical displacement of COM to be related to high-level skiers' superior oxygen cost compared to slower skiers (Zoppirolli et al., 2015). Because of gravity, it is conceivable that vertical alternation has the largest effect on oxygen cost in the V2 technique as well (Table 2).

Notably, vertical root-mean-squared acceleration in the latter part of the gliding phase ("middle pure glide"), affected oxygen cost and performance to the same extent as the full-cycle vertical root-mean-squared acceleration (Table 2). During this part of the glide phase, one ski is the only point of contact with the ground. This indicates benefit of smoother coordination of movements and improved balance. The possible performance enhancing implications of better balance are: (1) sufficient time for, and less energy demanding, repositioning of segments and equipment; (2)

longer time for recovery of propulsive muscles; and (3) possibly reduced friction on snow due to a flatter oriented ski.

Methodological considerations.

The 2D video analysis of the 3D nature of ski skating is a major limitation. However, the overall goal of this study was to characterize the timing of movements, and to analyse changes in technique along with changes in performance during a season. We find the longitudinal approach with mixed modelling and analyses of 2D video and accelerometer data, well suited for this purpose. To minimize the limitations of 2D video analysis, a skilled physiotherapist performed all video analyses chronologically for one participant at a time. The camera was positioned perpendicular to the skiing direction, and two laser beams forced the skiers to position at the middle of the treadmill. Upper arm, lower arm and leg length did not indicate any systematic errors (e.g. shoulder abduction) due to in-depth distance from the camera. A larger shoulder range of motion and a more extended elbow at pole plant, logically leads to a more forward pole plant and longer poling distance at constant speed. The video analysis and the poling time calculated from pole accelerometers confirmed this finding.

The technical variables were included one by one in the mixed model, because of the limited amount of tests and the fact that several of the variables (e.g. timing variables) are related. When comparing our hip results to centre-of-mass results, be aware of systematic errors (Myklebust et al., 2015). A final important remark is that hip IMU data do not reflect energy cost of basic physiological work (e.g. respiration), muscle work to maintain a position, non-optimal coordination of agonist and antagonist muscles, or moving limbs—all assumed to be included in the "oxygen cost" measure.

Conclusions

The findings of the present study may have direct practical implication for better understanding of the V2 technique. First, the V2 technique employed by elite skiers, revealed distinct timing sequences as the different joints were engaged in a “wave” pattern, starting with the hip and followed by joints in the legs and arms. Such "timing" is a key characteristic of the V2 technique and important for young skiers as regards to their long-term athlete development. Secondly, the finding of a likely small effect of vertical acceleration and cycle time on performance highlights the importance of a proficient balance. Finally, the present study indicates that IMUs can contribute in order to evaluate improvement of technique and performance.

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Table 1: Performance, physiological measures, and the technical parameters including full-cycle timing of phases, range of displacement (ROD) and root-mean-squared (RMS) acceleration in June and January at a fixed load (6°, 3.5 m·s^{-1}).

	June		January			Magnitude of differences (ES)	
1000-m time (s)	270	± 14	250	± 10	*	-1.63	Large
O_2-cost (mL/min)	4050	± 368	3769	± 388	*	-0.75	Moderate
Total mass (kg)	79.8	± 8.7	78.3	± 8.0	*	-0.18	Trivial
VO_{2peak} (mL/min)	5812	± 531	5776	± 522		-0.07	Trivial
Cycle time (s)	1.69	± 0.10	1.80	± 0.07	*	1.39	Large
Poling time (s)	0.70	± 0.04	0.75	± 0.04	*	1.16	Moderate
Poling time (% of cycle time)	42	± 2	42	± 2		-0.01	Trivial
Reposition time (s)	0.98	± 0.07	1.05	± 0.06	*	1.10	Moderate
Reposition time (% of cycle time)	57	± 1	57	± 2		0.07	Trivial
Kick time (s)	0.25	± 0.03	0.25	± 0.04		0.05	Trivial
Pure glide time (s)	0.73	± 0.05	0.80	± 0.06	*	1.24	Large
Poling distance (cm)	122	± 7	129	± 8	#	0.99	Moderate
Forward pole plant (cm)	18	± 9	24	± 8	*	0.78	Moderate
ROD sideways (cm)	32	± 8	40	± 6	*	1.14	Moderate
ROD AP (cm)	15	± 2	13	± 2		-0.78	Moderate
ROD vertical (cm)	14	± 3	14	± 2		0.15	Trivial
RMS sideways acceleration (m·s^{-2})	2.9	± 0.3	2.9	± 0.3		-0.14	Trivial
RMS AP acceleration (m·s^{-2})	3.4	± 0.5	3.1	± 0.3	*	-0.56	Small
RMS vertical acceleration (m·s^{-2})	3.0	± 0.3	2.7	± 0.4	*	-0.89	Moderate
RMS resultant acceleration (m·s^{-2})	5.6	± 0.5	5.2	± 0.4	*	-0.86	Moderate
RMS resultant acceleration pure glide (m·s^{-2})	4.4	± 0.5	3.9	± 0.4	*	-1.11	Moderate
RMS resultant acceleration poling (m·s^{-2})	6.1	± 0.8	5.7	± 0.7		-0.40	Small
RMS resultant acceleration kick (m·s^{-2})	7.1	± 0.7	7.0	± 0.7		-0.22	Small

Note: Data are mean ± standard deviation. AP = anterior-posterior direction. All technical parameters are from accelerometer analyses except for forward pole plant (relative to ankle position) which was calculated from video analysis. Total mass is body mass + equipment mass. ES = effect size. *Different from June ($P < 0.05$). # $P = 0.051$. N = 11, except for ROD and RMS accelerations where N = 10.

Table 2: Effect of technical variables on O_2-cost (slope) and performance (effect size = ES) derived from a mixed model adjusted for fixed effects of test time point and change in total mass, and allowing for random effects of participants.

	Slope	**CV**	**ES**		**Residual**
	% per %	**(%)**	**± 90 % CL**		**(%)**
Test time point					5.2
Total mass	0.92 ± 0.49	1.2	2.21 ± 1.18	moderate	3.9
Cycle time	**-0.18 ± 0.17**	**4.3**	**-1.50 ± 1.40**	**small**	**3.5**
Poling time	**-0.16 ± 0.15**	**5.0**	**-1.52 ± 1.28**	**small**	**3.4**
Pole reposition time	**-0.13 ± 0.17**	**4.3**	**-1.08 ± 1.41**	**small**	**3.7**
Kick phase time		6.2	-0.13 ± 1.08	unclear	4.0
Pure glide time	**-0.09 ± 0.12**	**5.9**	**-1.08 ± 1.43**	**small**	**3.7**
RMS acc sideways	0.06 ± 0.17	4.0	0.47 ± 1.32	unclear	3.9
RMS acc antero-posterior		7.3	-0.01 ± 1.26	unclear	4.0
RMS acc vertical	**0.10 ± 0.11**	**6.7**	**1.30 ± 1.36**	**small**	**3.6**
RMS acc resultant	0.09 ± 0.14	5.3	0.90 ± 1.45	unclear, possibly trivial to small	3.8
RMS acc vertical pure glide	0.05 ± 0.07	10.0	0.98 ± 1.26	possibly, small	3.7
RMS acc vertical late pure glide	0.03 ± 0.04	21.5	1.36 ± 1.48	small	3.6
RMS acc vertical poling	0.04 ± 0.08	7.9	0.61 ± 1.18	unclear, possibly trivial to small	3.9
RMS acc vertical kick	0.06 ± 0.08	7.2	0.85 ± 1.12	possibly, small	3.8
RMS acc resultant pure glide	0.08 ± 0.10	7.7	1.18 ± 1.49	small	3.7
RMS acc resultant middle pure glide	**0.05 ± 0.07**	**12.1**	**1.10 ± 1.53**	**possibly small**	**3.8**
RMS acc resultant poling		6.0	0.43 ± 1.21	unclear	3.9
RMS acc resultant kick		4.8	0.19 ± 1.12	unclear	4.0
Sideways ROD	-0.05 ± 0.05	13.0	-1.15 ± 1.30	small	3.7
Anterior-posterior ROD		15.2	-0.70 ± 1.29	unclear	3.9
Vertical ROD		7.2	-0.38 ± 1.31	unclear	4.0

Note: Data are mean ± 90% confidence limits. RMS acc = root-mean-squared hip acceleration. ROD = hip range of displacement. Total mass is body mass + equipment. CV is within- participants variation over the whole season and magnitude of effect size (ES) is calculated according to Hopkins et al. (2009) and Spencer et al. (2014). One technical variable was included at the time.

Figure legends.

Figure 1: Illustration of the examined joint angles. A = elbow, B = shoulder, C = hip, D = knee, E = ankle. Ankle joint angle was calculated from the following reference points: knee, ankle and the horizontal plane through the ankle joint.

Figure 2: Group mean joint angle characteristics for the elbow, shoulder, hip, knee and ankle during a full cycle in June and January. The cycle starts (0%) and ends (100%) at right pole plant during left ski thrust. The vertical full lines are right ski plant (18%) and liftoff (78 %). The vertical dotted lines are right pole plant (50%) and liftoff (70%). The right ski thrust phases are: I = gliding phase including the pure glide phase from ~28%, II = poling phase, and III = kick phase. The horizontal full line shows the area of differences between the June and January curves (paired t-test, $P < 0.05$, $N=11$).

Figure 3: Group mean curve of vertical acceleration (upper panel) and displacement (lower panel) measured by an accelerometer at the os sacrum (hip) in June and January. The cycle starts (0%) and ends (100%) at right pole plant during left ski thrust. The vertical full lines are right ski plant (18%) and liftoff (78 %). The vertical dotted lines are right pole plant (50%) and liftoff (70%). The right ski thrust phases are: I = gliding phase including the pure glide phase from ~28%, II = poling phase, and III = kick phase. The horizontal full line shows the area of differences between the June and January curves (paired t-test, $P < 0.05$, $N=10$).

Figure 4: O_2-cost at different test time-points (black line; mean ± 90% confidence limits; TP) and how models adjusting for total mass (body mass + equipment mass; TM), and technical factors (cycle time or root-mean-squared (RMS) vertical acceleration) modified the time-point effect. Remark that only two skiers were analyzed in June (II).

Figure 1.

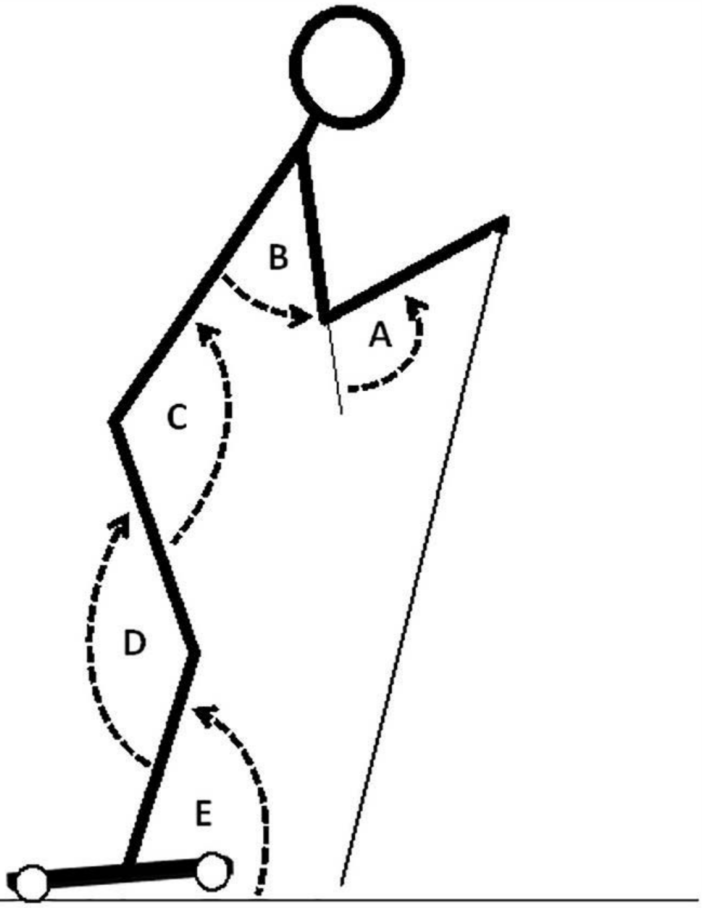
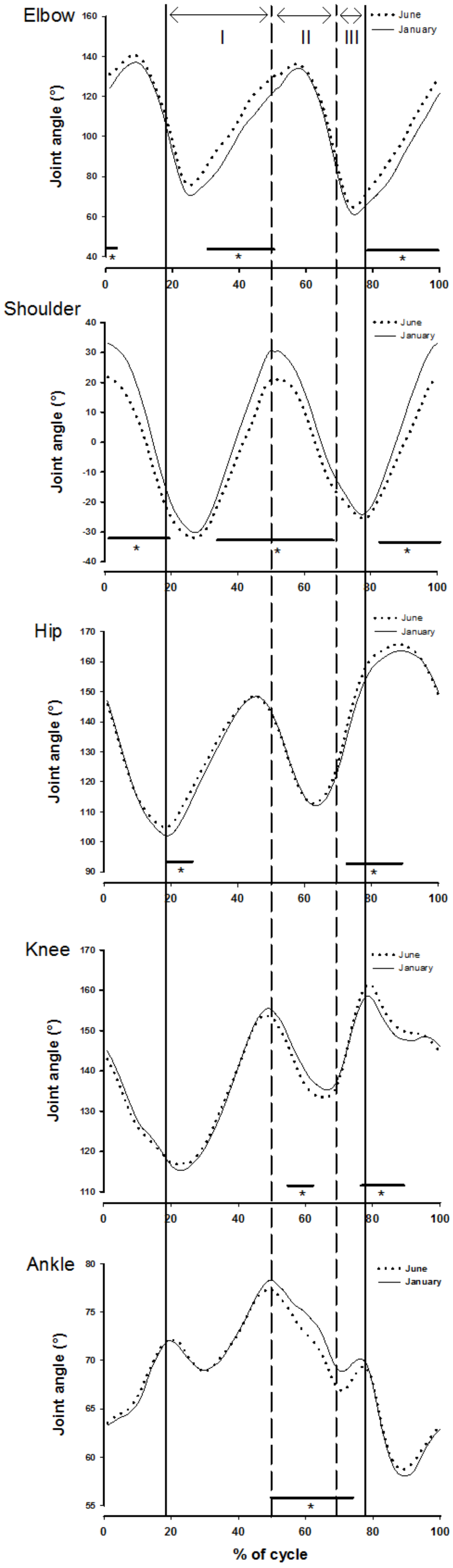


Figure 2.



Elbow
Shoulder
Hip
Knee
Ankle
Joint angle (°)
I
II
III
June
January
*
0
20
40
60
80
100
160
140
120
100
80
60
40
30
20
10
0
-10
-20
-30
-40
170
150
130
110
90
75
70
65
55
% of cycle

Figure 3.

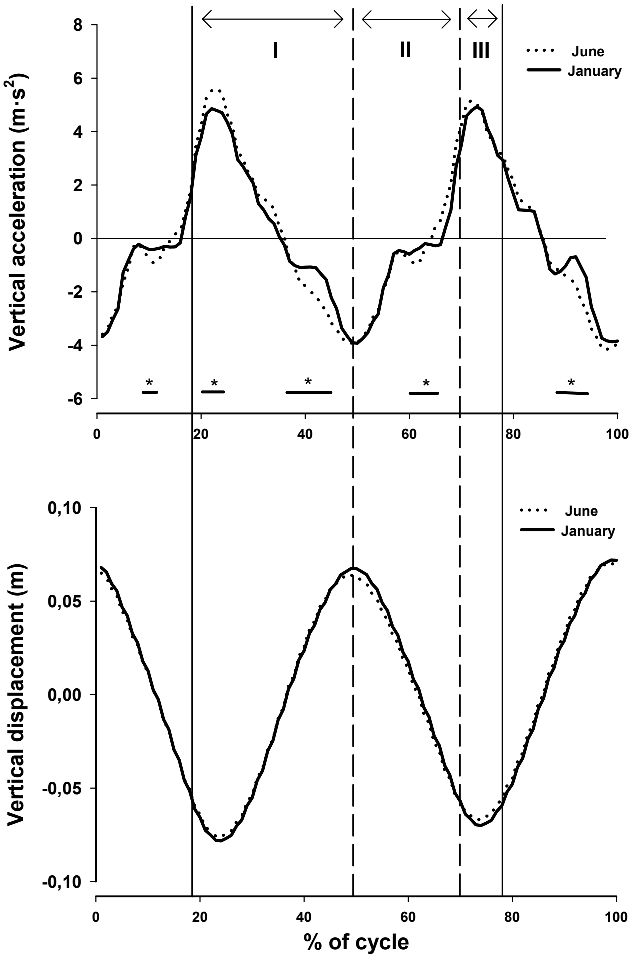
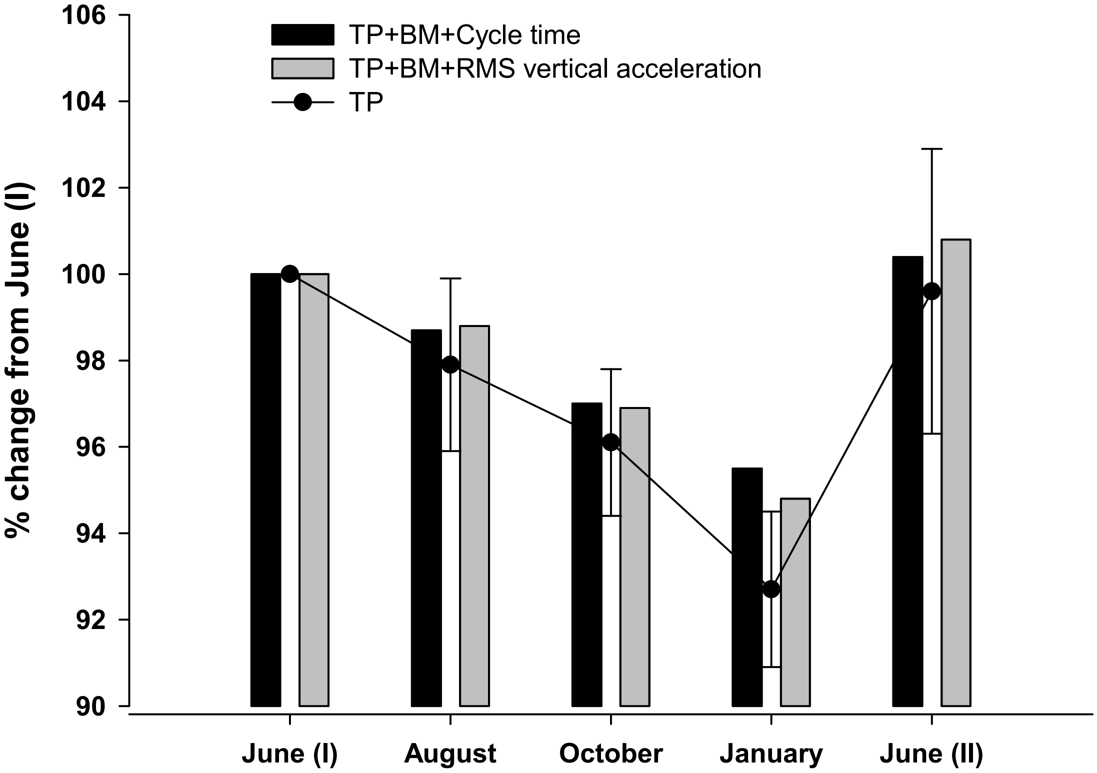

I
II
III
June
January
Vertical acceleration (m·s2)
8
6
4
2
0
-2
-4
-6
*
*
*
*
*
0
20
40
60
80
100
June
January
Vertical displacement (m)
0,10
0,05
0,00
-0,05
-0,10
0
20
40
60
80
100
% of cycle

Figure 4.


TP+BM+Cycle time
TP+BM+RMS vertical acceleration
TP
% change from June (I)
106
104
102
100
98
96
94
92
90
June (I)
August
October
January
June (II)

Paper IV