ANALYSING EFFECTIVENESS OF FORCE APPLICATION IN SKI SKATING USING FORCE AND MOTION CAPTURE DATA - A MODEL TO SUPPORT CROSS-COUNTRY SKIING RESEARCH AND COACHING

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Maastohiihto on huomattavan vaativaa kokovartaloliikuntaa niin fysiologian kuin biomekaniikankin kannalta tarkasteltuna. Latujen kunnostuksen, hiihtovälineiden, hiihtotekniikoiden sekä kilpailumuotojen kehityksen myötä hiihdosta on tullut nopeampaa ja vaativampaa, joka asettaa suurempia haasteita voimantuotolle. Vastaavasti hiihtotutkimuksessa huomio on viime vuosikymmeninä siirtynyt enemmän biomekaniikan suuntaan. Ensimmäiset ulkoisten suksi- ja sauvavoimien mittaukset suoritettiin yli kolmekymmentä vuotta sitten ja useita yhteyksiä voimantuoton ominaisuuksien ja hiihtosuorituskyvyn välillä on sittemmin tunnistettu. Edelleen on kuitenkin epäselvää mitkä ovat tärkeimmät voimamuuttujat kuvaamaan voimantuoton tehokkuutta, etenkin kolmiulotteista liikettä sisältävien luistelutekniikoiden osalta. Nykyiset voimamittaus-, liikekaappaus- sekä mittausaineiston käsittelyn teknologiat mahdollistavat kuitenkin tähän kysymykseen tarttumisen. Tässä tutkimuksessa on kehitetty ja testattu kolmiulotteista voima- ja liikeaineistoa hyödyntävä malli luisteluhiihdon voimankäytön tehokkuuden tarkasteluun. Mallissa käytetään uutta näkökulmaa, joka tarkastelee hiihtäjän massakeskipisteeseen suuntautuvia translationaalisia suksi- ja sauvavoimia sekä niistä laskettuja erisuuntaisia voimakomponentteja. Esimerkit mallin soveltamisesta kahden luisteluhiihtotutkimuksen aineistoon antavat viitteitä siitä, että mallin tulokset ovat oikeaa suuruusluokkaa mm. mitattuun kiihtyvyyteen suhteutettuna ja siten käyttökelpoisia luisteluhiihdon voimankäytön tehokkuuden tarkasteluun. Lisätutkimuksia laajemmin aineistoin kuitenkin tarvitaan tämän löydöksen vahvistämiseksi. Myös mallin sovellusta tulee kehittää, jotta se olisi tehokkaammin käytettävissä maastohiihdon, sekä vastaavia liikkeitä sisältävien lajien, tutkimuksen ja valmennuksen apuvälineenä.

Avainsanat: Maastohiihto, Luisteluhiihto, 3D liikeanalysi, Biomekaniikka, Propulsiovoima, Translationaalinen voima, Voimankäytön tehokkuus.

ABSTRACT

Mikko Pohjola (2014). Analysing effectiveness of force application in ski skating using force and motion capture data - A model to support cross-country skiing research and coaching. Department of Biology of Sport, University of Jyväskylä, Master's thesis, 68 pp.

Cross-country skiing is a whole body exercise posing significant physiological as well as biomechanical challenges. Due to developments in e.g. track preparation, skiing equipment, skiing techniques, and race types, cross-country skiing has become faster and more demanding with regard to production and application of force. Correspondingly, the emphasis in cross-country skiing research has shifted towards biomechanics during the recent decades. The first measurements of external ski and pole forces were made more than thirty years ago, and several associations between force characteristics and skiing performance have been identified ever since. However, it still remains unclear what are the most important variables characterising effective force application, particularly in the 3-dimensional movements of ski skating techniques? The development of force measurement, motion capture, and data processing technologies nowadays provide possibilities to tackle this question. In this research a model for analysing effectiveness of force application in ski skating using 3-dimensional force and motion data is developed and tested. The model employs a novel approach focusing on the translational ski and pole forces, directed to the skier's centre of mass, to estimating components of the skier generated forces in different dimensions. The examples of applying the model on data from two ski skating studies indicate that the model results are of correct order of magnitude e.g. in comparison to measured acceleration and thus plausible for analysing effectiveness of force application in ski skating. Further studies with more data are needed to confirm this finding. In addition, the model implementation shall be developed towards more efficient applicability in cross-country skiing research and coaching, as well as other sports involving similar movements.

Key words: Cross-country skiing, Ski skating, 3D motion analysis, Biomechanics, Propulsive force, Translational force, Effective force application.

ABBREVIATIONS AND DEFINITIONS

Anterior-posterior	Forward-backward from skier's point of view
Axial	Force acting in the direction of the pole shaft
COM	Centre of mass
COP	Centre of pressure
Cross	Across the longitudinal dimension of the ski
DW	Well-timed double arm swing, V2A skating without poles
EMG	Electromyography
$F_{med\text{-}lat}$	Medial-lateral force
F_{prop}	Propulsive force towards the intended skiing direction
$F_{propole}$	Propulsive force from poles
$F_{propski}$	Propulsive force from skis
F_R	Rotational force causing an angular moment in a body
F_{res}	Resultant force, sum of force components
F_T	Translational force moving the centre of mass of a body
F_1	Cross ski force acting across the ski
F_2	Longitudinal ski force acting along the ski
F_3	Vertical ski force acting perpendicular to ski surface
GRF	Ground reaction force
Medial-lateral	Across the intended skiing direction
PFA	Point of (ski or pole) force application
PFA-COM	Vector from point of force application to centre of mass
Pole force	Force applied through poles
Ski force	Force applied through skis
TW	Total weight of subject calculated as (body mass + skiing equipment mass + measurement system mass) * g
Vertical	Either perpendicular to ski surface or horizontal plane
V1 skating	Ski skating where a double pole push is performed asymmetrically on every second skating kick. Also known e.g. as offset and G2 skating.
V2 skating	Ski skating where a double pole push is performed symmetrically on every skating kick. Also known e.g. as G3 skating.

V2A skating	A variation of V2 with similar kicks, but a symmetrical double pole push is performed every second kick. Also known e.g. as open field and G4 skating.
WO	Without arm swing
XC-ski model	A motion analysis model for cross-country skiing, an extension of the plug-in-gait model included in the Vicon Nexus motion analysis software
1D	1-dimensional
2D	2-dimensional
3D	3-dimensional
α	edging angle between ski surface and track surface
β	orientation angle between longitudinal dimension of ski and skiing direction
γ	track incline angle

CONTENTS

1 INTRODUCTION

Cross-country skiing is a sport, in which the skier moves forward by means of forces applied through poles and skis. Such a whole body movement poses significant physiological challenges, e.g. to aerobic energy production and oxygen transportation, and correspondingly cross-country skiing has for long been a subject of interest in sport and exercise physiology (e.g. Saltin and Åstrand 1967). However, during the last decades cross-country skiing has gone through significant development in terms of skiing equipment, ski base and track preparation, skiing techniques, as well as race types (e.g. Kantola et al. 1985, Kataja et al. 1996, Rusko 2003), which has resulted in an increasing interest also in the biomechanics of skiing (e.g. Smith 1992, Holmberg et al. 2005, Lindinger et al. 2009, Zory et al. 2009, Ohtonen et al. 2013a). The most remarkable common factor behind the rise of cross-country skiing biomechanics is that the development of the sport has altogether resulted in significantly increased skiing speeds, causing a need for skiers to produce greater forces while having shorter times for their generation than earlier (cf. Stöggl et al. 2011). In addition, cross-country skiing, which could be considered as a four-legged gait somewhat resembling the movements of a horse (Killick and Herzog, 2010), poses significant challenges to the coordination of the movements in order to effectively direct and time the forces applied through skis and poles.

One of the most visible developments in cross-country skiing has been the introduction of ski skating style as an official cross-country technique during the 80's (Kantola et al. 1985, Smith 2003), although skating had been applied as a complementary technique in recreational and competitive skiing and ski orienteering where terrain and snow conditions allowed or required already for decades (Ohtonen 2010). Nowadays skating and classical styles are separated so that skating techniques (excluding step turn) are forbidden in classical ski races. A relatively comprehensive and up-to-date account of the currently applied classical and skating techniques is provided e.g. in the Olympic handbook of sport medicine: Cross-country skiing (Smith 2003), and the variety of different techniques is not described here in more detail. It must be noted, however, that since the publication of the book, the evolution of skiing techniques has continued, driven particularly by sprint skiing, resulting e.g. in a new double poling strategy (Holmberg et al. 2005), a double push V2 skating technique (Stöggl et al. 2008), and a diagonal running technique (Stöggl 2011).

The most important factors determining the speed of a cross country skier, particularly on flat and uphill sections, are the propulsive forces (i.e. forces moving the skier forward) generated by the skier and the drag forces (primarily air drag and ski-snow friction) resisting the movement of the skier along the track (Smith 2003). Whereas the drag forces are definitely important, often even decisive, factors for success in high-level competitions (Smith 2003), the performance differences between cross-country skiers are, however, in the long run mostly determined by their abilities to produce and maintain propulsive force during races. The understanding of force generation and the relationships between force characteristics and skiing performance is thus important for skier performance maximization, skier training optimization and skiing equipment development. These issues are considered in the following sections of this study, particularly with the aim to advance cross-country skiing research and coaching.

2 BIOMECHANICAL ANALYSIS OF CROSS COUNTRY SKIING

Traditionally, biomechanical research of cross-country skiing has been divided into relatively separate studies of kinematics, considering the characteristics of motion, and kinetics, considering the causes of motion (Smith 1992). In cross-country skiing, kinematics involves variables such as cycle velocity, rate, and length or joint angles and ranges of motion. Kinetics then looks into variables such as forces applied through skis and poles, muscle activity, or energy cost. However, already nearly thirty years ago Komi (1987) called for *"[...] a more comprehensive approach, in which muscle activity patterns and cinematographic analysis are integrated with the force records."* Fulfilling this vision has required development of measurement and data recording and analysis technologies, and only recently it has become feasible to conduct integrated studies of cross-country skiing bringing muscle activity and force measurements together with respiratory and blood sample measurements (e.g. Björklund et al. 2010, Halonen 2013) or motion analysis.

2.1 Measurement of forces in cross-country skiing

Measurement of forces in cross-country skiing is based on the three Newton's laws of classical mechanics: Law of Inertia, Law of Acceleration, and Law of Action-Reaction (Smith 2003). With this foundation, three different approaches have been used for measuring ground reaction forces (GRF) during cross-country skiing: 1) external force plates, 2) pressure insoles, and 3) force sensors mounted on skis and poles.

Force plates, covered with snow, have been used particularly for measuring both ski and pole forces in classical techniques, where the essential movements can be projected as

2-dimensional (2D) into antrior-posterior and vertical directions (e.g. Komi 1985, 1987, Vähäsöyrinki 1996, Vähäsöyrinki et al. 2008, Piirainen 2008, Mikkola et al. 2013). Also experiments in measuring ski skating forces with force plates have been made by Leppävuori et al. (1993). Force plates provide reliable force measurements in 2 or 3 dimensions, and once they are in place many skiers using their own equipment can be measured several times (Komi 1985, Leppävuori et al. 1993, Vähäsöyrinki et al. 2008). However, setting up of the measurement system is relatively time consuming and the application of force plates for studying the three-dimensional movements of ski skating is limited, particularly due to the spatial requirements of the measurement area.

A more recent approach to force measurement has been pressure insoles, which can be placed inside the ski boot (Holmberg et al. 2005, Lindinger et al. 2009, Stöggl et al. 2011). Pressure insoles consist of several smaller pressure measuring areas, whose results can be summed up as the total vertical (perpendicular to insole/ski surface) reaction force. In addition the approach allows convenient calculation of the location of the centre of pressure (COP), which can be considered as the point of force application (PFA). Pressure insoles are convenient to use and allows measurement of forces during skiing in normal conditions using either classical or skating techniques. The main limitations of this approach are that only the vertical ski force is measured.

Perhaps the most promising approach to measuring forces in cross-country skiing is to use force sensors in both skis and poles. In this approach, ski forces have been measured with small force plates placed between the ski and the ski binding (Ekström 1981, Komi 1987, Leppävuori 1989, Street & Frederick 1995, Babiel 2003, Ohtonen et al. 2013a), but also with strain gauges, measuring the bending strain, located under the roller ski (Hoset et al. 2013). Pole forces have mostly been measured with sensors placed under the handle (Ekström 1981, Leppävuori 1989, Street & Frederick 1995, Millet et al. 1998a, 1998b, Babiel 2003, Holmberg et al. 2005, Stöggl et al. 2006, Ohtonen et al. 2013b) or to the strap (Stöggl et al. 2006). The force plates between the ski and the binding allow measurement of ski forces in more than one dimension in both classical and skating techniques. Pole force is commonly measured only in the axial dimension (along the pole shaft), but also e.g. pole bending and temperature has been measured with strain gauges (Ekström 1981). At least the most recent ski and pole sensors allow natural skiing movements, can be conveniently moved from one set of skis and poles to another, and provide valid force measurements (Holmberg et al. 2005, Ohtonen et al 2013a).

2.2 Other aspects in biomechanical analysis of cross-country skiing

In addition to the development of force measurement systems, the enabling of the integrated biomechanical analysis of cross-country skiing has required developments also in several other measurement technologies. Some of the most essential are briefly reviewed below

One important factor in biomechanical analysis of cross country skiing is recognition and recording of motion for kinematic analysis. These technologies have developed from film cameras to digital video (Smith 1992, Street & Frederick 1995, Stöggl et al. 2008), and on to complete motion capture systems often involving reflecting markers placed on the study subject, infra-red-cameras for marker detection, and software for data recording and analysis (Stöggl & Holmberg 2011, Hoset et al. 2013). Such modern motion capture systems allow multiple and detailed recording of kinematic variables and make them readily analysable. On the other hand, the systems can be quite costly and their set up and use can turn out relatively time consuming. Correspondingly, another development path has evolved in so called non-marker motion capture, based on accelerometers, gyroscopes, inertial and other sensors allowing the detection of human movements and postures without cameras and markers (e.g. Godfrey et al. 2008, Marsland et al. 2012, Soipio 2013).

Also electromyographic (EMG) muscle activity recording has undergone significant development from needle electrodes to non-invasive surface EMG solutions (Hermens et al. 1999) and on to wearable EMG suits (Halonen 2013, Linnamo et al. 2013). Along with the increased convenience of EMG measurement, the level of scrutiny has also shifted from muscle fibres to whole muscles and eventually to functional muscle groups.

More generally, the development of wireless communication, and information technology in general has been an important enabler for the above mentioned developments in biomechanical analysis. For example, it has allowed the design of portable measurement devices, easier set-up of measurement sites in desired locations, as well as the extent (in terms of e.g. area, time, cycle count, number of variables) of measurement and analysis.

Furthermore, the introduction of ski tunnels with standardised weather and snow conditions has provided improved conditions for studying cross-country skiing on snow with real equipment (Linnamo et al. 2012) instead of roller-skiing on treadmill as is commonly done (e.g. Sandbakk 2013, Stöggl 2013). There are certain benefits in studying roller-skiing on treadmill related e.g. to the set-up of the measuring site, and roller-skiing is considered to be relatively representative of on-snow skiing. However, ski tunnels enable studying of skiing in even more realistic conditions.

Altogether, it can be considered that the above mentioned developments have resulted in a situation that the comprehensive approach advocated by Komi (1987) is currently possible to implement in cross-country skiing studies using both classical and skating techniques in realistic and standardised on-snow conditions. However, practical experiences and study results of implementing such an approach are still limited.

3 FORCE VARIABLES AND CROSS COUNTRY SKIING PERFORMANCE

Along with the development of measurement technologies, also the biomechanical phenomena contributing to cross-country skiing performance have been studied extensively. The first force measurements were made more than 30 years ago by Ekström (1981) and since then many associations between different force and cross country skiing performance characteristics have been identified. However, as forces in cross-country skiing (Table 1) are produced repeatedly in a cyclical manner, they must be considered in the context of different cycle characteristics (Table 2). In addition, the directions of forces are often considered in terms of their component resolutions in different dimensions, particularly in the intended skiing direction (propulsive forces).

TABLE 1. Examples of force characteristics considered in cross-country skiing studies.

Force characteristics	
Peak force	Highest value for force within a duty cycle.
Impulse of force	Product of the magnitude and application time of force.
Average force	Magnitude of force averaged e.g. over one cycle.
Time to peak force	Duration from the beginning of force application to peak force.
Impact force	Force resulting from the contact of ski or pole with track surface.
Push-off or active force	Force resulting from active force generation by the skier.

TABLE 2. Examples of cycle characteristics considered in cross-country skiing studies along with brief explanations.

Cycle characteristics	
Cycle time	Duration of a full cycle, e.g. from right ski lift off to right ski lift off.
Cycle length	The distance covered during one cycle.
Cycle rate / frequency	Number of cycles within a time unit, e.g. cycles / second.
Cycle velocity	Velocity during a cycle, e.g. calculated as cycle length / cycle time.
Work time / duty cycle	Duration of force application through poles or skis.
Recovery time	Duration between duty cycles.

3.1 Force vs. speed

Both vertical and anterior-posterior peak ski forces increase with speed in classical skiing (Komi 1985, Vähäsöyrinki 1996). In contrast, pole forces do not change much with speed in diagonal skiing, indicating greater proportion of propulsive ski force in higher speeds (Vähäsöyrinki et al. 2008). However, in the herringbone technique used in steep up hills, proportion of pole force has been found to increase significantly with increasing speed (Andersson 2011).

In double poling on roller skis, peak axial pole force and active peak force being higher than impact peak force are associated with higher sub-maximal speed (Holmberg et al. 2005). In addition, axial pole force was noticed equally predictive for double poling performance as its resolutions to vertical, anterior-posterior, and medial-lateral directions (Stöggl & Holmberg 2011). However, peak force and force impulse do not exclusively determine the maximal speed in roller ski double poling (Stöggl & Holmberg 2011).

In ski skating, peak resultant forces from both skis and poles have found to increase with speed in both V1 and V2 technique, while average forces remain nearly constant, when roller skiing in a 5º incline (Smith et al. 2006). Peak axial pole force and resultant ski force were found to increase also in V2 skating on snow in a 4º incline (Ohtonen et al. 2013c). However, in an earlier study, Leppävuori (1989) identified also average forces to increase with speed in both V1 and V2 technique in on-snow measurements in a 10º incline.

Altogether, increasing speed in cross-country skiing often involves increasing forces. However, it must be recognized that most often also cycle rates increase and force production times decrease along with increasing speed in all techniques. Correspondingly, different strategies based on increasing either force or frequency can be applied for speed increase in different conditions (cf. Ohtonen 2013b, 2013c).

3.2 Force vs. incline

In diagonal skiing, a small increase in vertical ski force, but a remarkable increase in anterior-posterior ski force is seen when moving from a small (2,5º) to a moderate (5,5º) incline, whereas in a steep incline (11º) both components decrease (Vähäsöyrinki 1996). As regards poling, both vertical and anterior-posterior force increase with increasing incline (Vähäsöyrinki 1996), but of particular importance seems to be the increase of the proportion of the anterior-posterior component partly due to the reduced pole inclination during force production (Pellegrini et al. 2011). In addition, the study by Lindinger et al. (2009) emphasizes the importance of the timing of pole force production in uphill diagonal skiing by showing an association between later occurrence of peak axial pole force and performance in maximal roller skiing test to exhaustion on a treadmill.

The increase of pole forces with increasing incline has been identified also in V1 skating by Millet et al. (1998a). Few other reports of studies on behaviour of ski skating forces in varying inclines seem to exist. However, Sandbakk et al. (2013) have found gross efficiency to be higher in V1 skating in a 12º incline than in V2 skating in a 5º incline at submaximal speeds with similar work rate.

Due to shorter glides in steeper inclines, cycle rates tend to increase with incline. However, at least for poling in diagonal skiing, the absolute force production times remain relatively constant although incline increases (Pellegrini et al. 2011). Similar behaviour can be assumed also for ski force production in both classical and skating techniques.

3.3 Force vs. friction

Friction has an important role in cross-country skiing e.g. in terms of grip properties in classical skiing as well as gliding properties in all techniques. The grip properties relate particularly to the anterior-posterior component of ski force in diagonal or double pole with kick techniques, good grip being associated with higher peaks in both vertical and anterior-posterior forces (Vähäsöyrinki 1996) as well as higher proportions of anterior-posterior force (Komi 1985, Piirainen 2008). Consequently, bad grip is associated with higher proportions of pole force in order to compensate for the lack of propulsion through skis (Vähäsöyrinki 1996, Piirainen 2008).

In ski skating Millet et al. (1998b) identified that higher rolling friction in roller skis resulted in higher average pole forces in comparable sub-maximal intensities on flat terrain. Increased pole force was found important in maintaining constant speed with a worse glide also by Ohtonen et al. (2013b) in an on-snow study using V2 skating in a constant 4° incline. In addition, higher cross ski force peaks, indicating greater angles between the ski and skiing direction, were identified in slow speeds in the same study (Ohtonen et al. 2013b).

Some similarities between the effects of friction and incline to force production can be seen. Better grip and greater incline both relate particularly to increased of anterior-posterior forces. On the other hand, in skating techniques worse glide as well as steeper incline are both compensated with increased force production, particularly in poling, as well as higher cycle rate (cf. Ohtonen et al 2013b).

3.4 Force vs. fatigue

In addition to above findings, some studies have also looked into the effects of fatigue to force production in cross-country skiing. In a sprint race simulation study using double poling, decreased axial pole forces and cycle rates were associated with decreased speed due to fatigue within and between heats (Mikkola et al. 2013). Correspondingly, Halonen (2013) noticed decreases in axial peak pole force, pole force impulse, average pole force, cycle rate, as well as muscle activity in several important muscle groups as a result of a simulated 6 km double poling race. Corresponding kinematic characteristics of double poling while fatigued were earlier identified also by Zory et al. (2009).

In a 20 km race simulation study using skating technique, small relative changes in vertical and cross peak ski force as well as peak axial pole force from pre-race sprint to post-race sprint were associated with good race performance (Ohtonen et al. 2012). Also in this study, cycle rate was found to decrease as a result of fatigue, but no correlations between cycle characteristics and race performance were identified (Ohtonen et al. 2012).

3.5 Force vs. technique

The above findings indicate that associations between force and performance characteristics are situation specific. Correspondingly, Stöggl et al. (2011) found that the relationships of strength and biomechanical characteristics with performance vary significantly between diagonal, double poling and V2 skating techniques. One reason may be that cross-country skiing consists of discontinuous movements and high degrees of freedom when coordinating the upper and lower extremities, allowing the use of different techniques in particular conditions they are best suited for (cf. Sandbakk et al. 2013).

For example, the proportion of anterior-posterior force from poles is higher in V2 than V1 skating, possibly due to a greater angle between the ski and the skiing direction in V1 (Smith et al. 2006). Furthermore V1 skating on roller skis is found to be physiologically advantageous to V2 skating in inclines greater than about 5º, possibly owing to the biomechanical differences between the techniques (Smith et al. 2006). On the other hand, V2 skating has been found to become physiologically advantageous in comparison to V1 skating on flat terrain when speed is increased from slow to moderate (Killick & Herzog 2010). Correspondingly it may be hypothesized that the above mentioned improved gross efficiency in steeper incline in ski skating found by Sandbakk et al. (2013) may be partly explained with the biomechanical differences between the different techniques used in different inclines (V2 in 5º, V1 in 12º).

However, perhaps the greatest difference between different cross-country techniques is that in the skating techniques force is applied on a gliding ski, while the kick in classical techniques takes place on a momentarily stationary ski. In practice it means for example that while force production times shorten along with increasing speeds, the times for producing ski forces in ski skating remain substantially longer than for producing pole forces or ski forces in classical kicks when approaching maximum speed. As a consequence, Killick & Herzog (2010) found that when speed is increased incrementally from slow to maximum in ski skating, skiers naturally first move from V1 to V2 technique, but again back to V1 when approaching the absolute maximum speed.

4 EFFECTIVE APPLICATION OF FORCE IN CROSS-COUNTRY SKIING?

Altogether, it appears that in cross country skiing increasing demands, whether in terms of speed, incline, or glide conditions, set increasing requirements for force production. However, it seems to be situation specific which force characteristics, e.g. force impulse, average force, peak force, time to peak force, or rate of force development, and in which dimensional components, are associated with better performance.

An issue mentioned in many study reports is *effective application of force*. Some attempts to defining it have also been made. For example, in diagonal and double poling techniques the late occurrence of peak axial pole force, coinciding with an advantageous pole orientation, seem to be an indication of effective force application (cf. Holmberg et al 2005, Lindinger et al. 2009, Pellegrini et al 2011, Stöggl & Holmberg 2011). In addition, Smith (2007) has suggested the proportion of propulsive component (i.e. towards skiing direction) in relation to the resultant force as a measure of effectiveness in cross-country skiing. A common factor in both of these definitions is the importance of the forward orientation of the ground reaction force (GRF), which can be considered as a tentative indicator of effective force production in cross-country skiing.

However, in the current shortage of comprehensive studies addressing the factors of effectiveness in cross-country skiing, it mostly still remains a mystery what effective application of force actually comprises of. Komi's (1987) statement from nearly 30 years back *”[t]he final question, however, concerns what one wants to analyze from the force records of the skis and poles. [...] Cross-country skiing is such a complex activity that identifying the important functional components is often difficult”*, is still descriptive of the current situation. Particularly, there seems to be a need to understand force production in the 3-dimensional (3D) movements of ski skating.

Some complementary insight can be sought from other sports having some comparable characteristics with regard to cross-country skiing. In speed skating it has been found that the push-off force and performance are not associated, but high power production, indicated by a small angle between the push-off leg and horizontal (referred to as effectiveness) is (de Boer et al. 1986, de Koning et al. 1987, Figure 1a). In accelerated running, further forward oriented ground reaction forces and improved acceleration performance are found to coincide with further forward oriented body positions, while on the other hand the body position also affects the angular moments to the body caused by gravity and ground reaction force (Kugler & Janshen 2010, Figure 1b). Correspondingly, in ski jumping research it has been found that the ground reaction force during take-off can be decomposed into a translational component acting through the centre of mass and a rotational component causing an angular moment to the body (i.e. $F = F_T + F_R$) (Schwameder 2008, Figure 1c).

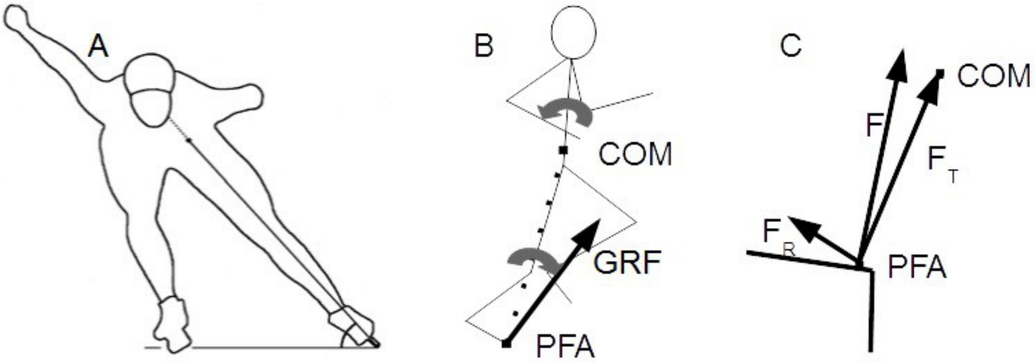

FIGURE 1. A. In speed skating, the angle between push-off leg and horizontal is considered as effectiveness (adapted from Noordhof et al. 2013). B. In accelerated running, body position, represented by the line between point of force application (PFA) and centre of mass (COM), affects the direction of ground reaction force as well as the angular moments caused by gravity and ground reaction force (adapted from Kugler & Janshen 2010). C. In ski jumping, take-off force (F) can be decomposed into a translational component (F_T) acting through the COM and a rotational component (F_R) causing an angular moment to the body (adapted from Schwameder 2009).

Also these findings emphasize the importance of the direction of the ground reaction force. In addition, they also bring forward the importance of the body position, both independently as well as in relation to the direction of force. Consequently, it can be considered that both force direction and body position are potentially important determinants of effective application of force in cross-country skiing, and thereby variables worth considering alongside e.g. magnitudes of forces and cycle characteristics in biomechanical analyses of cross-country skiing. Thus far the studies considering propulsive forces in cross-country skiing have focused on determination of force magnitudes and directions, perhaps together with ski and pole orientation, but without account of body position (e.g. Hoset et al. 2013, Leppävuori 1993, Mikkola et al. 2013, Pellegrini et al. 2011, Smith et al. 2006 , Street and Frederick 1995, Stöggl and Holmberg 2011, Vähäsöyrinki et al. 2007).

5 AIMS OF THE STUDY

The aim of this study was to develop and test a model for estimating ski and pole forces and analysing characteristics of effectiveness of force application in ski skating using 3D force measurement and motion capture data. The ultimate goal is to produce a tool for studying ski skating effectiveness in cross-country skiing research and coaching.

However, as mentioned above, it is still far from clear which aspects of force production and application are most crucial in different situations and how do they link to observed performance characteristics? Therefore, the goal in this study has been to develop the model as comprehensive and flexible to address a variety of potentially important factors regarding how the skier generated forces move the skier forward. Correspondingly, the model development and testing has been guided by following questions addressing both application of the model in force effectiveness analysis (1-4) and its implementation in the broader context of measurement and analysis (5-7):

1. Is resolution of ski and pole forces into directed components important and useful for characterising effectiveness of force application in ski skating?
2. Is resolution of ski and pole forces into translational and rotational components applicable in analysing effectiveness of force application in ski skating?
3. Can ski and pole force direction or body position be used as indicators for effectiveness of force application in ski skating?
4. Can estimates of propulsive components be used as predictors of skier's motion?
5. Is it important to measure ski GRF in more than one (vertical) dimension?
6. How crucial is the accuracy of COM and PFA location estimates for calculating translational forces?
7. Is pole bending necessary to take account of in pole force component calculation?

6 MATERIALS AND METHODS

6.1 Data collection

The data used in developing and testing the model were collected in two ski skating studies. *Fatigue* study looked into how fatigue cumulated during a simulated 20 km ski skating race affected the kinematics and kinetics of V2 skating. *Swing* study examined arm swing effects on performance, kinematics, and kinetics in ski skating without poles.

6.1.1 Fatigue study

In the fatigue study, nine elite male skiers (28.4 ± 6.3 years, 176 ± 4.5 cm, 74.5 ± 5.7 kg) participated in a simulated 20 km cross country skiing race using skating technique. Race was performed in Vuokatti ski tunnel (Finland) where the temperature (-4 Cº) and humidity (85 %) were kept constant. One 70 meter maximum speed sprint in the last uphill (4° incline) of the track was performed using V2 skating technique before (pre-sprint) and immediately after the race (post-sprint).

Axial pole forces were measured with light weight force sensors mounted inside the pole grip/tube (Velomat, Germany, Figure 2a). Ski forces were measured with custom made 2-dimensional (vertical and cross) force measurement system (University of Jyväskylä, Finland) based on strain gauge technology, and placed between the ski and ski binding using the Rottefella (Rottefella as, Klokkarstua, Norway) NIS (Nordic Integrated System) binding system (Figure 2b).

From the force bindings and pole force sensors, the data was transferred via cables to a 8-channel ski force amplifier (University of Jyväskylä, Finland). Force data was collected at a 1 kHz sampling rate with a data collection system consisting of an A/D converter and a wireless transmitter WLS-9163 (National Instruments, Austin, Texas, USA), which transferred the data to a portable computer equipped with a wireless receiver card and custom made data collection software (Labview 8.5; National Instruments, Austin, Texas, USA). The amplifier, A/D card, were placed on the subject's waist in custom made waste bag. The weight of the data collection system was 2170 g comprising of 490 g (front 290 g, rear 200g) for each force binding, 70 g for each pole sensor, and 1050 g for the backpack containing the remaining parts of the system. Despite the small increase in the skiing equipment as well as the total weight, it can be considered that the data collection system did not affect the skiing of any subject.

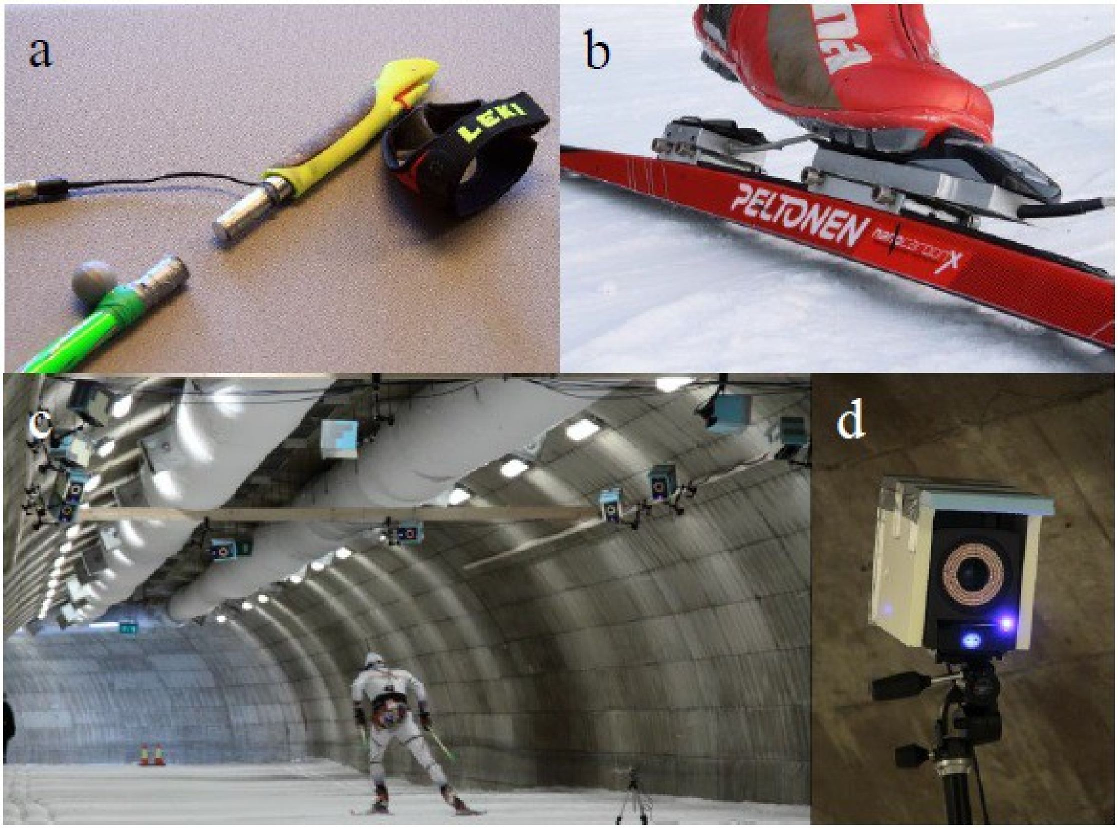

FIGURE 2. Measurement equipment used in the studies: pole force sensor under the pole grip and a reflecting pole marker attached to the pole shaft (a), ski binding sensor mounted between the ski and the binding (b), camera set-up and a subject within the measurement area (c), and one infra red camera covered with isolation box (d).

3-dimensional motion data was collected at 100 Hz sampling rate using 12 infra-red cameras (Vicon, Oxford, UK, Figure 2c,d) and 41 reflecting markers placed on the subject (Plug-in-Gait marker set) and 10 on the equipment (3 in each ski and 2 in each pole), and Vicon Nexus 1.7.1 software (Vicon, Oxford, UK, Figure 3). The cameras covered an area of 15 meters allowing recording of one skiing cycle. For synchronization of force and motion data, a trigger signal was simultaneously recorded into both data collection systems every time a subject was within the measurement area.

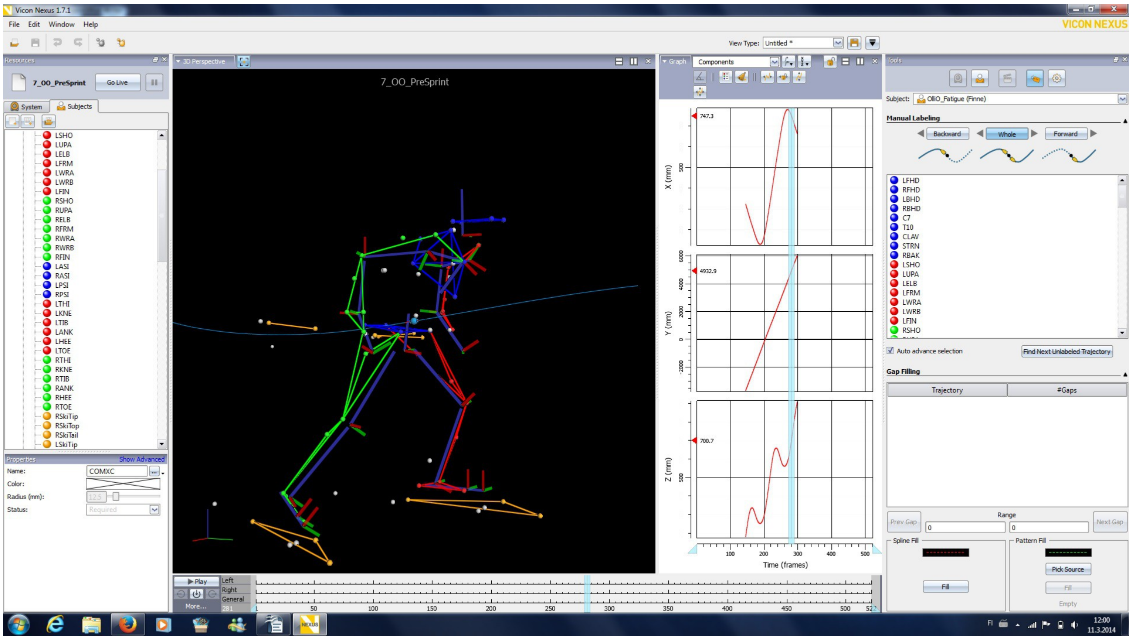

FIGURE 3. A screen shot of the Vicon Nexus 1.7.1 software showing a motion analysis model of a cross-country skier in the fatigue study. The two markers on each pole and the three markers on each ski used to detect pole and ski positions are connected as pole and ski body segments with yellow lines.

All subjects used similar carbon-fibre racing poles (weighing 190 g each), adjusted to right length for each subject, and the same pair of skis (Peltonen Supra-x, Peltonen Ski Oy, Hartola, Finland, 1170 g each), which were prepared similarly to minimize friction (race waxing) before measurement of each subject. The coefficient of friction for the skis was measured with a custom made ski tester (University of Jyväskylä. Finland, Linnamo et al. 2009) as 0.028. The coefficient of friction was used as a multiplication factor to estimate the longitudinal force from the measured vertical force and thus providing the third force dimension.

In addition, muscle activities for main muscle groups involved in ski skating were recorded with an EMG suit (Myontec Oy, Kuopio, Finland) using the same data collection system as for force data. However, EMG data analysis is not considered here.

6.1.2 Swing study

In the swing study, eleven highly skilled male elite skiers (30 ± 8 years, 177 ± 6 cm, 76.2 ± 6.1 kg) performed ski skating without poles on a nearly flat section of Vuokatti ski tunnel at sub-maximal and maximal speeds with different techniques: a) well-timed double arm swing, b) badly timed double arm swing, c) single arm swing, and d) without arm swing. Conditions, equipment, and data collection were as in the above described fatigue study, with some alterations as described below.

While one ski (left) was equipped with a 2D force binding as in the fatigue study, the other ski (right) was equipped with a 2D force binding measuring ski forces in vertical and longitudinal directions. As the ski tester was not used in this study, the longitudinal force measurement was used to determine the coefficient of friction for the trials analysed here as 0.035. The coefficient of friction was used as a multiplication factor to estimate the longitudinal force from the measured vertical force.

In addition to the force bindings, ski force data was collected with Pedar pressure insoles (Novel, Germany). This provided another measurement of the vertical (perpendicular to ski surface) force as a point of comparison to the forces measured with the force bindings. In addition an estimate of the location of centre of pressure representing the point of force application was provided.

Motion data was collected with 16 infra-red cameras, allowing recording of two to three skiing cycles. Two extra markers were placed on the subject (mid-sternum, mid-spine) to ensure the visibility of sufficient amount of markers during all phases of the cycle.

The ski skating techniques used in this study did not involve poling, so no recording of pole forces and movements was needed. The subjects used their own skis and the force bindings were moved from a pair of skis to another for the measurement of each subject.

6.2 Data processing

Data for two subjects, comprising of Pre- and Post-sprint trial data and race results, were chosen for analysis from the fatigue study. Subject A was placed 3rd and subject B was placed 7th in the 20 km ski skating race. A noticeable performance difference in both sprinting speed and race result, as well as a remarkable difference in reduction of sprinting speed due to fatigue, was observed between these subjects (Table 3).

From swing study, data from two trials for one subject were chosen for analysis. The other trial involved skating without arm swing at maximal speed (WO), and the other involved skating with well timed double arm swing (imitating the movement of V2A skating) at sub-maximal speed (DW). This subject C used the same skis as were used in the fatigue study. The speeds in the two trials applying differing techniques were approximately the same, allowing comparison between techniques. The anthropometric, trial and performance data for all subjects are presented in table 3.

3D motion data from the trials was initially processed with Vicon Nexus 1.7.1 software (Vicon, Oxford, UK, Figure 3) using standard labelling and gap-filling procedures and the plug-in-gait model (PIG) included in the software. In addition, a custom made XC-ski model (University of Salzburg, Austria), written in BodyLanguage script, was used. The XC-ski model is an extension of the plug-in gait model including poles and skis.

TABLE 3. Anthropometric, trial and performance data for subjects A and B chosen for analysis from the fatigue study and subject C chosen for analysis from the swing study. Total weight (TW) was calculated as (body mass + skiing equipment mass + measurement system mass) * g.

Subject	Height [cm]	Total weight [kg]	Incline [°]	Coefficient of friction	Pre-sprint velocity [m/s]	Post-sprint velocity [m/s]	20 km time [h.min:s]
A	182.5	93.8	4	0.028	6.71	5.89	59:25
B	173.5	80.0	4	0.028	5.81	4.46	1.01:47

Subject	Height [cm]	Total weight [kg]	Incline [°]	Coefficient of friction	WO velocity [m/s]	DW velocity [m/s]
C	175.0	80.1	1	0.035	5.72	5.93

Then motion data was merged and synchronized with force data and processed with Ike Master 1.38 software (IKE Software Solutions, Salzburg, Austria). Merged motion and force data were used to determine the orientation and edging angles of the skis, pole orientation, COM location, speed and acceleration in relation to the 1D pole and 3D ski forces.

Next, a model for analysing characteristics of effective force application (see results for a detailed description) was developed and implemented as formulas written in the Ike Master formula editor. The model was then used for calculating resultant ski and pole forces and their component resolutions along the axes of the global coordinate system determined for motion capture. In addition, the locations of pole and ski PFA were estimated and used with COM location for calculating the translational components of pole and ski forces and their resolutions along the coordinate axes. In both studies the xy-plane was set as horizontal, with y-axis in the skiing direction, and z-axis perpendicular to the horizontal plane. Consequently, the propulsive force components in the skiing direction were resolved from the vertical (z) and anterior-posterior (y) components taking account of the track incline.

The model results were then used to consider potential associations between force characteristics and differences between subjects, pre- and post-sprints and different techniques in light of the performance and cycle characteristics of different trials. The specific questions on effectiveness of force application explored with the model were chosen according to the research questions presented in the aims of the study as follows:

1. Can the performance differences between subjects (A and B) and performance or technique changes within subjects (A, B, or C) be seen as differences in force component estimates (resultant, medial-lateral, anterior-posterior) with or without resolution of GRF into translational and rotational components?

2. Can the performance differences between subjects (A and B) or performance or technique changes within subjects (A, B, or C) be seen as differences in PFA-COM direction, GRF direction independently or their relative orientations?

3. Are the propulsive force component estimates provided by the model of plausible magnitude in comparison to the measured velocity and acceleration of the skier?

For all questions, the analysis of fatigue study trials focused on one ski and one pole push-off on the right side. For swing study trials, the analysis was made from one ski push-off on left side where vertical and cross forces were measured with force bindings.

In order to answer question 3, an estimate for the total propulsion for one cycle was needed. As V2 skating was used in the fatigue study this was calculated assuming similarity of ski and pole push-off between right and left side (2 identical ski push-offs and 4 identical pole push-offs in a cycle). For swing study data, question 3 was considered only for the symmetrical WO trial (2 identical ski push-offs in a cycle). For all trials, the calculated propulsive ski force component was considered effective only during the active push-off phases of ski-snow contact, and during the glide phase the only effective ski force was assumed to be friction force (i.e. longitudinal ski force). The average velocity was considered approximately constant across cycles for all trials. The air drag was assumed to be 10 N for all trials (cf. Smith 2003). The influence of gravity was calculated as TW*sin(γ), where TW is total weight, calculated as (body mass + skiing equipment mass + measurement system mass) * g, and γ is the track incline. For the analyses regarding question 3, the data was exported to and processed in Open Office Calc 4.0.0.

6.3 Validation and evaluation

6.3.1 Force measurement systems

The 2D force binding system has been validated by Ohtonen et al. (2013a) against measurements with standard force plates, pressure insoles and a custom made long force plate area (University of Jyväskylä, Finland, Mikkola et al. 2013) and found to be reliable and accurate in measuring the vertical and cross forces as well as vertical and longitudinal forces in cross-country skiing. The calibration of the system was performed according to the procedure described by Ohtonen et al. (2013a). The pole force measuring system as well the pressure insole system have been validated by Holmberg et al. (2005) and found sufficiently accurate for measuring pole and plantar forces produced in cross-country skiing. The calibration of the systems were performed according to the procedures described by Holmberg et al. (2005).

6.3.2 Motion analysis models

Although a relatively commonly used model, a validation study of the plug-in-gait model was not found in public research literature. Instead, it has been found to produce a systematic error in the COM location estimate in the anterior-posterior direction (Kugler & Janshen 2010). The error was corrected in the XC-ski model using a calculated location of the T12 vertebra, instead of L5, as the point for separating the trunk into pelvis + abdomen and thorax segments (cf. Winter 1990).

The estimates for COM location from plug-in-gait model and XC-ski model without skis and poles were evaluated against measurements with an AMTI force plate (Advanced Mechanical Technology Inc, Watertown, Massachusetts, USA). The floor projections of the COM estimates of the models were compared to COP estimates of the force plate in various postures imitating skiing without skis and poles. The mean distance from the force plate COP was 84.4 mm for the PIG model and 6.0 mm for the XC-ski model without skis and poles. The COM location estimates were also evaluated in the vertical direction against measurements with a COM scale (University of Salzburg, Austria), but no significant differences between scale measurements and model estimates were found. The COM estimates of the XC-ski model were considered to be sufficiently reliable and accurate for the purposes of this research.

The XC-ski model assumes no bending of the poles during pole push-off and estimates the location of the pole tip (i.e. pole PFA) using the locations of the finger marker, pole markers and pole length. This results in moving of the modelled pole tip up to approximately 100 mm during pole push-off, although in reality the pole tip remains virtually fixed. Therefore, the modelled pole tip locations in the beginning of the pole-snow contact, when no remarkable force is yet applied on the pole and no remarkable bending yet occurs, were used as the pole tip (= pole PFA) locations during pole force application for all fatigue study trials involving poling.

6.3.3 Force application effectiveness model

Due to a small sample size, statistical analysis can not be meaningfully applied on the results obtained with the model. The model results were thus only compared to findings of earlier studies where applicable (see discussion). However, some analyses considering model behaviour with variation in certain essential parameters were made. These analyses, addressing the implementation of the model in the broader context of data collection and analysis, are described below and their results are presented in the results section.

One important question is how ski forces are measured and how the force measurement method influences the model results. In order address this, corresponding ski force characteristics were calculated for 2D (vertical and cross) and 1D (vertical) force binding measurements as well as for 1D (vertical) pressure insole measurement and compared against 3D force measurements for one trial (WO) where pressure insoles were used.

Another important question relates to the estimation of COM and ski PFA locations. In this regard, the sensitivity of the model was tested for variation in these parameters. The alternative COM locations considered were from a) plug-in-gait model, and b) XC-ski model without skis and poles. The alternative ski PFA locations were obtained from i) pressure insole measurement and ii) assuming PFA as a fixed point in the centre of the sole plane. Also this test was done on one trial (WO) where pressure insoles were used.

A third important question relates to the pole bending during pole force application. In order to address its potential importance, the angles for the line from pole PFA to COM and the axial pole force were calculated at the moment of peak axial pole force in the anterior-posterior-vertical plane. In addition, pole bending during peak force was estimated in two ways. The first way assumed the line from pole PFA to pole head as the bottom of an equilateral triangle with legs of ½ pole length, and calculated its base angle from the distance between pole PFA and pole head using data from the XC-ski model. In the second way forces between 0-275 N were applied to a comparable pole as used in the trials, positioned on an AMTI force plate (Advanced Mechanical Technology Inc, Watertown, Massachusetts, USA) in an approximately 60 degree angle to the horizontal plane. The pole was equipped with three reflective markers and bending was estimated from the displacement of the lowest marker (60 mm from the pole tip) using motion capture data recorded with a comparable set-up as used in the fatigue and swing studies.

In the end, the model and its implementation in the overall measurement and analysis practice were evaluated following an adaptation of the ”properties of good assessment” -framework (Pohjola & Tuomisto 2007, Sandström et al. in press, Table 4). The overall evaluation grading the model in terms of different properties on a three-point scale (low, moderate, high) is provided in the discussion section.

TABLE 4. Framework for evaluating the force application effectiveness model and its implementation. Adapted from the properties of good assessment -framework (Pohjola & Tuomisto 2007, and Sandström et al. in press).

Category	Attribute	Explanation
Quality of content	Informativeness & Calibration	How specific, exact and correct are the model results?
	Coherence	How well does the model address its intended questions?
Applicability	Relevance	How well do the model and results serve the needs of users?
	Availability	Are model and results available when and where needed?
	Usability	Are model and results comprehensible and usable to users?
	Acceptability	Are data collection, processing and assumptions acceptable?
Efficiency	Internal efficiency	How much effort was needed to use the model in a study?
	External efficiency	How much can the model be made use of in other studies?

7 RESULTS

7.1 Force application effectiveness model

The main result of this research is the calculative model for estimating translational ski and pole force components and indicators of force application effectiveness using force measurement and motion capture data. The general form of the model can be formulated as following two equations (explanations of the terms in Table 5):

$$F_{TXYZski} = (((F_1 + F_2 + F_3) \cdot (PFA - COM / |PFA - COM|)) * (PFA - COM / |PFA - COM|)) \cdot (X, Y, Z)$$

$$F_{TXYZpole} = (((F_1 + F_2 + F_3) \cdot (PFA - COM / |PFA - COM|)) * (PFA - COM / |PFA - COM|)) \cdot (X, Y, Z)$$

The model thus first calculates the axial pole force and resultant ski force vectors. These are obtained using pole and ski force measurement data, pole marker location coordinates and ski angles from the motion capture data.

Next the model calculates the translational component vectors of axial pole and resultant ski forces directed from the PFA to the skier COM, i.e. the translational resultant forces. The pole PFA (location of the pole tip during force application) and the COM coordinates are obtained from the motion capture data. Ski PFA coordinates are calculated from the distribution between front and rear force binding measurements as (1-front/total) * sole length. This local value is then related to the global coordinate system by means of ski angles and the location of the front end of the binding (as local origin) obtained from the motion capture data. Alternatively, the ski PFA can be determined from the pressure insole COP correspondingly.

Eventually, the model calculates the component of translational ski and pole forces in the desired direction, e.g. propulsive forces in the skiing direction. The components can be calculated also directly from the resultant and axial forces by skipping the calculation of their translational components. In addition, several other variables can be calculated by omitting or reorganizing parameters (see examples of model application below).

TABLE 5. Explanations of the terms in the pole and ski force component equations.

Term	**Explanation**
$\mathbf{F_{TXYZpole/ski}}$	Translational component of pole/ski force in the direction (X, Y, Z).
$\mathbf{F_{pole}}$	Axial pole force acting along the pole shaft.
$\mathbf{F_1}$	Cross ski force acting across the ski.
$\mathbf{F_2}$	Longitudinal ski force acting along the ski.
$\mathbf{F_3}$	Vertical ski force acting perpendicular to ski surface.
PFA-COM/|PFA-COM|	Direction vector from point of force application to centre of mass.
$\cdot$	Dot (mathematical operator) indicating calculation of scalar product.
(X, Y, Z)	Point vector along which the force component is calculated.

As an example, the components of the translational ski and pole forces of V2 skating along the y-axis (positive values forward, in and up from the skier's perspective) of the global coordinate system can be written out as:

$$F_{Xski} = |F_1| \cos\alpha \cos\beta + |F_2| \sin\beta \cos\gamma + |F_3| \sin\alpha \cos\beta$$

$$F_{Yski} = |F_1| \cos\alpha \sin\beta \cos\gamma - |F_2| \cos\beta \cos\gamma + |F_3| \sin\alpha \sin\beta \cos\gamma$$

$$F_{Zski} = -|F_1| \sin\alpha \cos\gamma - |F_2| \sin\gamma + |F_3| \cos\alpha \cos\gamma$$

$$\begin{aligned} F_{TYski} = {} & (((F_{Xski}) * (X_{COM} - X_{PFA}) + (F_{Yski}) * (Y_{COM} - Y_{PFA}) + (F_{Zski}) * (Z_{COM} - Z_{PFA})) * (Y_{COM} - Y_{PFA})) \\ & / ((X_{COM} - X_{PFA})^2 + (Y_{COM} - Y_{PFA})^2 + (Z_{COM} - Z_{PFA})^2) \end{aligned}$$

$$\begin{aligned} F_{TYpole} = {} & ((|F_{pole}|) * ((Y_{top} - Y_{end}) * (Y_{COM} - Y_{PFApole}) + (Z_{top} - Z_{end}) * (Z_{COM} - Z_{PFApole})) * (Y_{COM} - Y_{PFApole})) \\ & / ((Y_{COM} - Y_{PFApole})^2 + (Z_{COM} - Z_{PFApole})^2 * \sqrt{(X_{top} - X_{end})^2 + (Y_{top} - Y_{end})^2 + (Z_{top} - Z_{end})^2}) \end{aligned}$$

where:

F_{XYZski} = components of measured ski forces along the coordinate axes

α, β, γ = ski edging angle, ski orientation angle, track incline angle,

X_{COM}, Y_{COM}, Z_{COM}, X_{PFA}, Y_{PFA}, Z_{PFA} = global coordinates of COM and ski or pole PFA,

X_{top}, Y_{top}, Z_{top}, X_{end}, Y_{end}, Z_{end} = global coordinates of the higher and lower pole markers.

It is worth noting that, because poling in V2 skating can be assumed to take place approximately symmetrically on both sides of the body, the PFA of the total poling force in the above example is considered to lie approximately on the same level as the COM in the medial-lateral dimension (x-axis). The pole PFA-COM vector is thus abstracted into the yz-plane and its x-coordinates are omitted in the calculation of the translational pole force.

7.2 Examples of model application

The model was applied to scrutinize the aforementioned questions regarding effectiveness of force application in ski skating. First, the resultant ski force, its propulsive component, and medial-lateral component were calculated both with and without consideration of body position, i.e. resolution of translational force, for all trials (Table 6). Second, corresponding pole force calculations were made for the trials involving poling (Table 7). Third, some potential indicators of force application effectiveness were calculated (Table 8). Then the force-time curves and indicator values were considered in light of performance and cycle characteristics in order to identify possible associations with fatigue as well as performance and technique differences. Eventually, the propulsive force estimates were used to estimate the total average propulsion over one full cycle for all trials involving symmetrical ski skating techniques and compared to the forces resisting the progression of the skiers (Table 9).

7.2.1 Ski and pole forces

Basic performance and cycle characteristics as well as peak values for the resultant (F_{res}), propulsive (F_{prop}), and medial-lateral ($F_{med\text{-}lat}$) ski forces with and without resolution of translational force (F_T) are presented for all six trials in Table 6. For subject A and B the cycle rates decrease and push-off times increase while fatigued. However, in the technique change from no arm swing to well-timed double arm swing for subject C, decreased cycle rate and increased push-off time come occur along with higher force levels.

Figure 4 shows a comparison of subject A pre and post trial force-time curves for resultant ski force (F_{res}), its propulsive component (F_{prop}), and the translational propulsive force (F_{Tprop}). Fatigue in the post-sprint shows as an increase in both glide and push-off time. At the same time, force levels remain comparable for F_{res} and F_{prop}, but a decrease is seen for F_{Tprop} (see Table 6 for peak values).

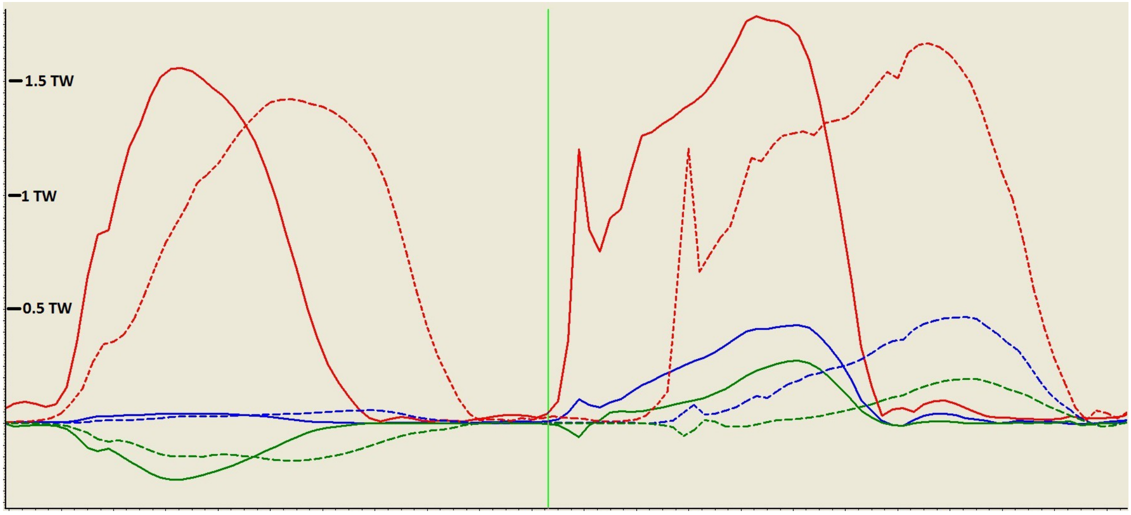

FIGURE 4. Subject A force-time curves of pre-sprint (solid line) and post-sprint (dashed line) trials for the resultant ski force (F_{res}, red), the propulsive component calculated directly from resultant ski force (F_{prop}, blue), and the translational propulsive component (F_{Tprop}, green). Green vertical line indicates the beginning of push-off phase for the pre-sprint trial force-time curves. Both glide time and push-off time increase as a result of fatigue, but a decrease of peak force level takes place only for F_{Tprop}. Negative values for F_{Tprop} during the glide phase indicate backward inclination of the line from the point of force application to the centre of mass (PFA-COM) during glide phase. However, the actual ski force affecting the skier movement during the glide phase is the ski-snow friction force. TW = total weight calculated as (body mass+skiing equipment mass+measurement system mass) * g.

When considering the results from all trials (Table 6), the differences in resultant and translational resultant forces (F_{res} and F_{Tres}) as well as translational propulsive force (F_{Tprop}) seem to be in line with both inter-individual performance differences and intra-individual performance change due to fatigue.

Particularly, the pre-post performance change for subject B, paralleled with a collapse of F_{Tprop}, stands out from the results. Also the technique change from no arm swing to well-timed double arm swing during push-off shows as an increase in the same forces. No other indications of potential associations were observed.

TABLE 6. Comparison of peak values for resultant (F_{res}), propulsive (F_{prop}) and medial-lateral ($F_{med\text{-}lat}$) ski forces estimated with or without resolution of the translational force (F_T). In addition, velocity, cycle rate and push-off time for each trial is provided. Also intra-individual differences between trials are calculated. Force values are expressed as multiplication factors of subjects' total weight (TW) calculated as (body mass+skiing equipment mass+measurement system mass) * g.

Trial	Velocity [m/s]	Cycle rate [1/s]	Push-off time [s]	F_{res}	F_{prop}	$F_{med\text{-}lat}$	F_{Tres}	F_{Tprop}	$F_{Tmed\text{-}lat}$
A pre	6.71	0.75	0.34	1.79	0.43	0.95	1.76	0.27	0.80
A post	5.89	0.64	0.44	1.67	0.47	1.06	1.60	0.19	0.70
Change [%]	-12.2	-14.7	29.4	-6.7	9.3	11.6	-9.1	-29.6	-12.5
B pre	5.81	0.71	0.43	1.69	0.63	1.32	1.47	0.20	0.60
B post	4.46	0.60	0.55	1.41	0.31	0.88	1.34	0.05	0.60
Change [%]	-23.2	-15.5	27.9	-16.6	-50.8	-33.3	-8.8	-75.0	0.0
C WO	5.72	0.73	0.30	1.98	0.36	1.38	1.91	0.21	0.88
C DW	5.93	0.68	0.38	2.18	0.41	1.54	2.05	0.28	0.90
Change [%]	3.7	-6.8	26.7	10.1	13.9	11.6	7.3	33.3	2.3

The corresponding characteristics for pole forces are presented in Table 7. The medial-lateral components were excluded being of less relevance regarding pole forces.

TABLE 7. Comparison of peak values of axial (F_{pole}) and propulsive ($F_{proppole}$) pole forces estimated with or without resolution of the translational force in the anterior-posterior-vertical plane (F_T). In addition, velocity, cycle rate and poling time for each trial, as well as differences between pre- and post-sprint for are provided. Force values are expressed as multiplication factors of subjects' total weight calculated as (body mass+skiing equipment mass+measurement system mass) * g.

Trial	Velocity [m/s]	Cycle rate [1/s]	Poling time [s]	F_{pole}	$F_{proppole}$	F_{Tpole}	$F_{Tproppole}$
A pre	6.71	0.75	0.36	0.30	0.21	0.28	0.13
A post	5.89	0.64	0.39	0.22	0.18	0.21	0.13
Change [%]	-12.2	-14.7	8.3	-26.7	-14.3	-25	0.0
B pre	5.81	0.71	0.30	0.28	0.22	0.27	0.18
B post	4.46	0.60	0.30	0.28	0.20	0.28	0.17
Change [%]	-23.2	-15.5	0.0	0.0	-9.1	3.7	-5.6

The indications of potential associations with performance or technique differences are less clear than those for ski forces, but subject A exhibits an expected increase in poling time along with a decrease in resultant pole force (F_{pole}), its propulsive component ($F_{poleprop}$), and translational resultant pole force (F_{Tpole}), as a result of fatigue. However, no change in the translational propulsive force (F_{Tprop}) is observed. In contrast, subject B appears to have maintained the poling capacity almost on the same level from pre-sprint to post-sprintc consodering all forces.When considering the ski and pole forces in aggregate, it appears that the two trials having nearly same velocity using the same technique, A post and B pre, also have similar force characteristics with regard to resultant and propulsive forces (Figure 5). In addition, the cycle rates, push-off times, and poling times are somewhat comparable.

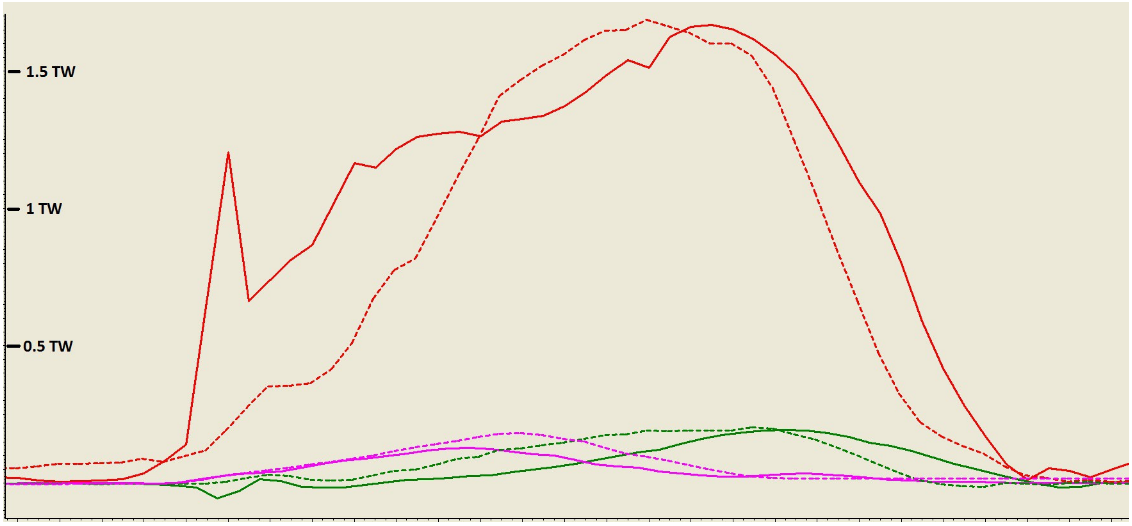

FIGURE 5. Force-time curves of resultant ski force (F_{res}, red), translational propulsive ski force (F_{Tprop}, green), and translational propulsive pole force ($F_{Tproppole}$, pink) during the ski and pole push-off phase for subject A post-sprint (solid line) and subject B pre-sprint (dashed line). The trials have nearly equal velocities and in addition a relatively high degree of similarity in force characteristics can be observed.

7.2.2 Force effectiveness indicators

Values for some tentative indicators of force application effectiveness, which can be derived from intermediate results of the model calculations, are presented in Table 8. These indicators characterise the direction of the ski and pole ground reaction forces in anterior-posterior and medial-lateral directions ($F_{ant\text{-}post}$, $F_{med\text{-}lat}$, $F_{poleant\text{-}post}$), and body position, as direction of translational resultant force, during force application in anterior-posterior and medial-lateral directions ($F_{Tant\text{-}post}$, $F_{Tmed\text{-}lat}$, $F_{Tpoleant\text{-}post}$). The indicators are expressed as lengths of the y- and x-axis oriented components of the corresponding unit vectors ($F_{res}/|F_{res}|$ or $F_T/|F_T|$). In addition, the interrelation between force direction and body position is characterized as translational to resultant/axial force ratios (F_{Tres}/F_{res}, F_{Tpole}/F_{pole}).

TABLE 8. Comparison of indicators for force direction, body position, and their interrelation during force application in light of inter-individual performance differences and intra-individual performance or technique changes. Values are given at the moment of peak resultant ski force (F_{res}) or axial pole force (F_{pole}) as lengths of unit vector components. Corresponding values at the moment of peak translational propulsive force (F_{Tprop} or $F_{Tproppole}$) are provided in brackets.

Trial	Velocity [m/s]	$F_{ant\text{-}post}$	$F_{med\text{-}lat}$	$F_{Tant\text{-}post}$	$F_{Tmed\text{-}lat}$	F_{Tes} / F_{res}	$F_{poleant\text{-}post}$	$F_{Tpoleant\text{-}post}$	F_{Tpole} / F_{pole}
A pre	6.71	0.17 (0.20)	0.52 (0.56)	0.07 (0.10)	0.41 (0.47)	0.99 (0.99)	0.65 (0.69)	0.36 (0.41)	0.94 (0.94)
A post	5.89	0.22 (0.25)	0.61 (0.68)	0.05 (0.07)	0.43 (0.47)	0.96 (0.94)	0.76 (0.78)	0.55 (0.58)	0.95 (0.95)
B pre	5.81	0.30 (0.36)	0.74 (0.83)	0.07 (0.10)	0.41 (0.47)	0.87 (0.80)	0.73 (0.76)	0.60 (0.63)	0.99 (0.98)
B post	4.46	0.17 (0.19)	0.63 (0.68)	-0.04 (-0.02)	0.44 (0.50)	0.95 (0.95)	0.64 (0.74)	0.51 (0.61)	0.99 (0.98)
C WO	5.72	0.16 (0.17)	0.67 (0.69)	0.10 (0.10)	0.45 (0.46)	0.96 (0.96)			
C DW	5.93	0.18 (0.19)	0.71 (0.75)	0.11 (0.17)	0.45 (0.51)	0.94 (0.95)			

With regard to ski forces, the GRF direction as well the translational to resultant force ratio at peak resultant force do not seem to have strong explanatory value for inter-individual performance differences, intra-individual performance change, or intra-individual technique change. However, the direction of the F_T, characterizing body position, appears to be potentially associated with intra-individual performance change, as decreased forward inclination and increased sideways inclination at the moment of peak F_{Tprop} appear in parallel with decreased performance due to fatigue for both subjects A and B. Particularly the change in $F_{Tant\text{-}post}$ is noticeable, showing a backward inclination in relation to the horizontal in the post-sprint. In addition, an indication of a possible relationship between anterior-posterior inclination and technique for subject C can be seen.

As regards pole forces, no clear indications of potential associations can be observed. However, it may be considered that the high F_{Tpole}/F_{pole} ratio for subject B in both pre-sprint and post-sprint is in line with the earlier notion of his ability to keep up efficient pole force production even when fatigued.

7.2.3 Propulsion vs. resistive forces

The final endeavour in the search for characteristics of effective force application was related to testing the plausibility of the propulsive force estimates provided by the model. The estimates for propulsive ski, pole and total forces as well as resistive forces (air drag, gravity) averaged over one cycle for the trials involving symmetrical techniques are presented in Table 9.

The results indicate that whereas the propulsive components calculated directly from the resultant and axial forces (F_{prop}, $F_{proppole}$) seem to provide 2-3 fold overestimates of the average forces moving the skier forward, the translational propulsive components (F_{Tprop}, $F_{Tproppole}$) appear to be quite consistently of the right order of magnitude across all trials. In the translational estimates, the greatest difference of -25 N average force observed for subject B is equivalent to approximately -0.3 m/s^2 average acceleration during the cycle, corresponding to a velocity difference of approximately -0.5 m/s between the beginning and end of the cycle.

TABLE 9. Estimated propulsive and resistive (air drag, gravity) forces averaged over one cycle and compared. Values given for translational propulsive ski and pole forces. Values for propulsive components calculated directly from the resultant or axial force provided in brackets.

Trial	**Resistive forces [N]**	**F_{Tprop} (F_{prop}) [N]**	**$F_{Tproppole}$ ($F_{proppole}$) [N]**	**$F_{Tproptotal}$ ($F_{proptotal}$) [N]**	**Difference [N]**
A pre	74	38 (93)	46 (79)	84 (172)	10 (98)
A post	74	22 (99)	53 (72)	75 (171)	1 (97)
B pre	65	30 (116)	59 (78)	89 (194)	24 (129)
B post	65	-5 (70)	45 (59)	40 (129)	-25 (64)
C WO	24	19 (47)		19 (47)	-5 (23)

The acceleration predicted from the translational propulsive ski force-time curve for subject C also shows considerable agreement with the measured acceleration of the skier's centre of mass with regard to magnitude (Figure 6.). However, the shapes of the predicted and measured acceleration curves are not identical. Particularly noticeable is the timing difference of approximately 0.1 s between the propulsive force peak and measured acceleration peak.

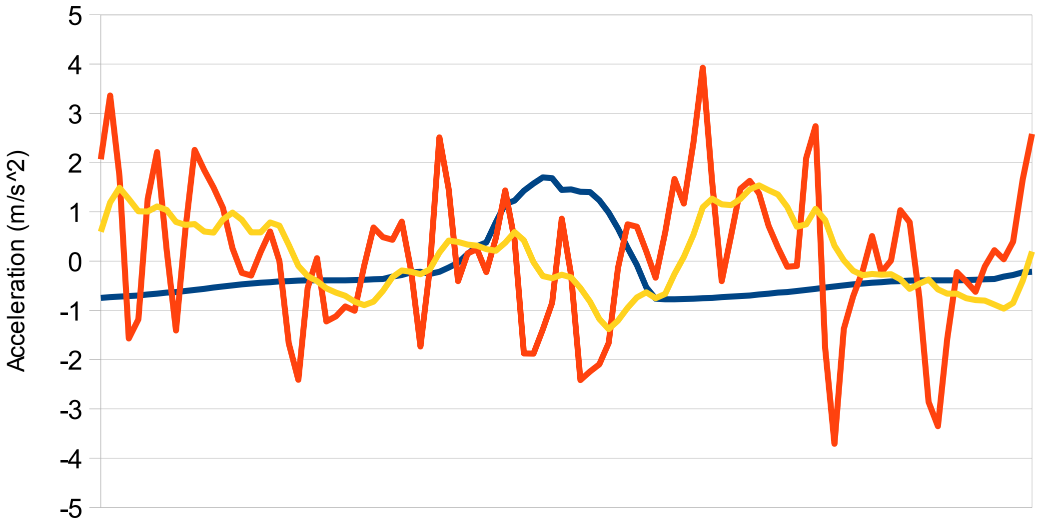

FIGURE 6. Acceleration towards intended skiing direction of subject C (WO trial) predicted from the translational propulsive ski force (F_{Tprop}, blue line) around one push-off (time frame = 1 s) in comparison to the measured acceleration of COM obtained from the motion capture data (orange line) and its 10 point moving average (yellow line). The predicted acceleration is of approximately correct magnitude, but the peaks of predicted and measured acceleration do not coincide. The estimated F_{Tprop} is assumed to be effective only during the push-off, while only the friction force (longitudinal ski force) is assumed to be effective during the glide phase.

7.3 Analyses regarding model implementation

In addition to applying the model to scrutinize characteristics of effective force application, analyses were made in order to guide future implementation of the model in the broader context of measurement and analysis of cross-country skiers. These mostly relate to the sensitivity of the model regarding certain important parameters of the model.

7.3.1 1-3D ski force measurements

One important question is how skier generated forces are measured and how the force measurement method influences the model results. In order to address this, the peak resultant ski forces (F_{res}), its propulsive (F_{prop}), and medial-lateral ($F_{med\text{-}lat}$) components with and without resolution of the translational force (F_T) were calculated for 2D (vertical and cross) and 1D (vertical) force binding measurements as well as pressure insole measurement and compared against 3D measured forces for the WO trial from subject C (Table 10).

TABLE 10. Comparison of peak resultant (F_{res}), propulsive (F_{prop}) and medial-lateral ($F_{med\text{-}lat}$) with and without resolution of translational force calculated from 3-dimensional measurement (vertical and cross) and estimation (longitudinal) of forces (3D), 2-dimensional measurement (vertical and cross) of forces (2D), 1-dimensional measurement (vertical) of force (1D) with force bindings, and 1-dimensional measurement (vertical) with pressure insoles (1D*). All values for subject C WO trial. The differences in relation to 3D are provided in brackets. Force values are expressed as multiplication factors of subjects' total weight calculated as (body mass+skiing equipment mass+measurement system mass) * g.

	F_{res}	F_{prop}	$F_{med\text{-}lat}$	F_{Tres}	$F_{Tmed\text{-}lat}$	F_{Tprop}
3D	1.98	0.36	1.38	1.91	0.88	0.21
2D	1.98 (0.0 %)	0.43 (19.4 %)	1.36 (-1.4 %)	1.90 (-0.5 %)	0.88 (0.0 %)	0.21 (0.0 %)
1D	1.97 (-0.5 %)	0.37 (2.8 %)	1.14 (-17.4 %)	1.94 (1.6 %)	0.90 (2.3 %)	0.22 (4.8 %)
1D*	1.89 (-4.5 %)	0.35 (-2.8 %)	1.10 (-20.3 %)	1.87 (-2.1 %)	0.87 (-1.1 %)	0.21 (0.0 %)

In this example, the number of dimensions considered in force measurement seem to have remarkable importance only regarding $F_{med\text{-}lat}$ (1D and 1D* vs. 3D) and F_{prop} (2D vs. 3D). However, in the translational forces, these differences level out. With regard to all other forces, the differences seem relatively small.

7.3.2 COM and PFA estimates

Another important question is how the locations of centre of mass (COM) and point of ski force application (PFA) are estimated and how does their accuracy influence model results. In order to analyse this, two alternative locations for both COM and ski PFA were determined and used to calculate the translational resultant (F_{Tres}), propulsive (F_{Tprop}), and medial-lateral ($F_{Tmed\text{-}lat}$), forces for the WO trial from subject C, and compared to results corresponding values calculated as described above (Table 11).

The alternative COM locations were from the XC-ski model without skis and poles and the Plug-in-Gait model. The alternative ski PFA locations were from Pedar pressure insole estimate for COP location and a fixed point in the centre of the sole plane. The comparison of forces and displacements against the XC-ski model were made at the moment of peak F_{Tres}.

The results indicate that altogether the differences are small for F_{Tres}, noticeable for $F_{Tmed\text{-}lat}$, and remarkable for F_{Tprop}. Leaving out poles and skis while estimating COM location with the XC-ski model, does not seem cause a big error either in the COM location or the force estimates. For the other alternatives especially displacement of the y-coordinate as well as the overestimation of F_{Tprop} is remarkable.

TABLE 11. Comparison of the translational resultant (F_{Tres}), propulsive (F_{Tprop}), and medial-lateral ($F_{Tmed\text{-}lat}$) ski forces calculated based on two alternative estimates for both the location of point of force application (PFA) and the centre of mass (COM). XC-ski = PFA and COM location estimated as explained above. COM XC-ski no skis & poles = COM estimated with XC-Ski model without consideration of skis and poles. COM Plug-in-gait = COM estimated with the Plug-in-Gait model included in the Vicon Nexus software version 1.7.1. PFA Pedar = PFA estimated with Pedar pressure insoles. PFA midsole = PFA estimated as a fixed point in the centre of the sole plane. All values for subject C WO trial. Differences, provided in brackets, are expressed in relation to XC-ski. Force values are multiplication factors of subjects' total weight calculated as (body mass+skiing equipment mass+measurement system mass) * g. Positive values for displacement are inward (x) and forward (y) from the point of view of the skier.

	F_{Tres}	F_{Tprop}	$F_{Tmed\text{-}lat}$	**Displacement (X,Y) [mm]**
XC-ski	1.91	0.21	0.88	
COM XC-ski no skis & poles	1.90 (-0.5 %)	0.19 (-9.5 %)	0.87 (-1.1 %)	(5, -8)
COM Plug-in-Gait	1.93 (1.0 %)	0.40 (90.5 %)	0.96 (9.1 %)	(20, 91)
PFA Pedar	1.89 (-1.0 %)	0.34 (61.9 %)	0.79 (-10.2 %)	(36, -54)
PFA midsole	1.90 (-0.5 %)	0.40 (90.5 %)	0.82 (-6.8 %)	(22, -75)

7.3.3 Pole orientation and pole force direction

A third important question relates to pole bending during force application. In order to address this, the angles during peak pole force were calculated for the pole PFA-COM and the axial pole force in the yz-plane for the four trials involving poling. In addition, pole bending during peak force was estimated in two ways. The results are in Table 12.

TABLE 12. Angles for the line from the point of pole force application to skier centre of mass (pole PFA-COM) and axial pole force. In addition results for two ways to estimate pole bending at peak axial pole force bending. Bending 1 estimate is from modelled shortening of the line from pole tip to pole head. Bending 2 estimate from displacement of pole markers during pole force application on a force plate. Values are averages for the four trials involving poling.

	Angle / bending at peak pole force [°]
Pole PFA-COM	59
Axial pole force	46
Bending 1 (pole tip-head distance)	14
Bending 2 (275 N at 60°)	14

The results imply that at peak axial pole force the modelled direction of the axial pole force is on average approximately 13 degrees further forward inclined from the pole PFA-COM, while the actual direction of axial pole force may be another 14 degrees further forward inclined due to pole bending.

In terms of errors in force estimates, this would mean that at the moment of peak axial force the force effectiveness model may underestimate the propulsive pole force component calculated directly from the axial pole force by approximately 20 %. At the same time, the translational propulsive component may be overestimated by approximately 5 %. Before and after the peak force these errors would likely be smaller.

8 DISCUSSION

In following, the model, the results from its application, and the implementation of the model in the broader context of measurement of analysis are discussed and eventually evaluated in light of the properties of good assessment -framework (Table 4).

8.1 Model application

This research was a pilot study in which the force application effectiveness model has been developed iteratively and applied to a broad set of questions with a limited set of data in order to test the functioning of the model. Consequently, the model results can not be considered as conclusive answers to the questions identified as important based on the literature review and listed in the aims of the study. Instead, the results shall be interpreted as indicating which variables of potential interest and importance shall be taken for further scrutiny and guiding the application of the model in future studies.

Because of the small data set, statistical analyses can not be meaningfully applied here. However, in comparison to relevant previously published results regarding external forces produced in cross-country skiing, the results seem to be of reasonable magnitude e.g. with regard to peak resultant ski forces (Hoset et al. 2013, Ohtonen et al. 2013b) and peak axial pole forces (Ohtonen et al. 2013b) in ski skating, as well as peak propulsive pole forces in double poling (Mikkola et al. 2013). On the other hand, some of the estimated average propulsive ski and total forces, particularly for the fatigue study trials, seem somewhat higher than comparable results in literature (Hoset et al. 2013, Smith et al 2006). This may result from differences in study settings, e.g. roller skiing vs. on-snow, race pace vs. full speed, 1D vs. 3D ski force measurement, and varying track inclines. In addition, the estimates of pole bending are greater than what was measured by Stöggl et al. (2011) in double poling.

The force comparisons are however possible regarding the estimated values not based on the resolution of translational force. Instead, the approach of resolving the translational ski and pole forces directed to the skier's centre of mass, in essence considering the skier as a rotating body, before calculating the components in different dimensions (Tables 6-7, Table 9) is novel in ski skating research and no results with same approach have been previously presented. However, the approach seems intuitively plausible and theoretically builds on previous research findings regarding ski jumping (Schwameder, 2009) and running (Kugler and Janshen, 2010). In addition, the comparisons of average propulsive force estimates from the model against estimated resistive forces (Table 9) and measured acceleration (Figure 6) provide support to the plausibility of the approach.

However, it must be noted that there is significant uncertainty related to the assumed similarity between sides and push-offs. For example, it may be questioned if the analysed individual pole push-off in subject A pre-sprint or the ski push-off in subject B post-sprint are necessarily representative of the corresponding trials as whole? Nevertheless, it seems that the characteristics of the translational propulsive forces, as estimated with the model, may be worth consideration alongside the more conventional force variables analysed in ski skating studies. For example, the considerations regarding efficiency differences between ski skating techniques in varying inclines and speeds (Killick and Herzog 2010, Sandbakk et al. 2013, Smith 2006) and double poling strategies (Holmberg et al. 2005) could be enlightened with inclusion of this perspective. In comparisons between ski skating techniques it could also be useful to consider the effectiveness of force application and body position in relation to the direction of the subsequent ski glide (with varying orientation angles between techniques) instead of the intended skiing direction.

Similarly, no counterparts for the force effectiveness indicators presented in Table 8 can be found from published ski skating research, but the concept of effectiveness in force application developed for speed skating (de Boer et al. 1986, de Koning et al. 1987) bears resemblance. However, here an increase particularly in anterior-posterior inclination (forward) of the push-off leg, or the line from PFA to COM, was identified as potentially associated with increased performance in ski skating. In contrast to speed skating, the increased inclination in medial-lateral dimension would appear to indicate decreased performance in ski skating. On the other hand, it is possible that in fact the effectiveness of force application did improve from pre-sprint to post-sprint for both subject A and B, but the performance still dropped as a result of compromised power production due to fatigue (cf. Table 8). Further exploration with more samples, including more analysed push-offs per trial, would be needed to resolve the usefulness of these body position indicators.

8.2 Model implementation

Some of the greatest concerns regarding the model relate to the estimation of its certain important parameters having remarkable influence to the model results. Particularly the estimated locations of PFA and COM are critical as the whole translational force approach is based on being able to determine the orientation of the PFA-COM line, along which the translational force is acting. According to the simple sensitivity analysis addressing alternative ski PFA and COM locations (table 11), the model is quite sensitive to these parameters, especially in the anterior-posterior dimension influencing the translational propulsive force estimates.

In the validation study the COM estimates provided by the XC-ski model were found relatively accurate, and much more accurate than the COM estimates provided by the original plug-in-gait model. It must still be recognized that the XC-ski model has not been validated taking account of the extra masses of skis, poles and measurement equipment used in this study. On the other hand, the differences in COM location and translational force estimates between the XC-ski model and XC-ski model without skis and poles was identified as small in the sensitivity analysis (Table 11).

Instead, the correctness of the ski PFA location estimates used in the application examples is less clear, although the model results do seem reasonable. It is noteworthy that in the model sensitivity analysis, the difference in ski PFA location, and consequently translational force estimates, in comparison to that obtained with the established method of Pedar pressure insoles is remarkable. Further analyses would be needed to resolve which approach to estimating ski PFA location would actually be most reliable and accurate.

The pole PFA location is less problematic as its modelled location can easily be compared with the observed actual location of the pole tip. Nevertheless, space for improvement exists in how pole movements are modelled with the XC-ski model and pole force directions are calculated with the force effectiveness model, particularly with regard to pole bending. However, according to the analysis (Table 12) the magnitude of error in the translational force estimates due to the lack of explicit account of pole bending remains quite small.

8.3 Overall evaluation of the model

8.3.1 Quality of content

The results of the model application involve a high degree of uncertainty due to a small sample size and open questions related to some of its critical parameters as well as some of the assumptions incorporated into the model. However, despite these uncertainties, the model and its results succeed to indicate some potentially useful variables deserving further consideration in future studies addressing ski skating effectiveness. Altogether, the *informativeness* and *calibration* of the model can thus be considered moderate.

The model also succeeds to provide somewhat reasonable answers to all of the questions it was intended to address, and appears to be conceptually plausible. The *coherence* of the model can thus be considered relatively high.

8.3.2 Applicability

According to the literature review, the questions addressed by the model are essential for studying the effectiveness of force application in ski skating. To a great extent these questions have also remained unanswered. The model, in fact, introduces a whole new approach to studying ski skating effectiveness. It can thus be considered a highly *relevant* contribution to advancing knowledge in this field.

There are, however, some essential limitations related to the application of the model. The model itself employs basic trigonometry and vector algebra, and can be easily applied in different computational platforms. Instead, the implementation of the model in this research builds on availability of simultaneously recorded 3D force and motion data, whose collection requires specific measurement equipment, data processing tools, as well as some skills. Consequently the *availability* of the model itself could in principle be high, but as regards its implementation in this research, the *availability* may be considered relatively low.

As the model employs relatively simple calculations, the interpretation of model results is quite straightforward. However the uncertainties regarding parameters and assumptions of the model, as discussed above, make drawing conclusions from the results more challenging. Altogether, the *usability* can be considered moderate.

The uncertainties regarding model assumptions can be considered as somewhat descriptive of the current limitations in the general understanding about the associations between force characteristics and ski skating performance. Instead, the parameter uncertainties as well as the compromised model availability mostly relate to how successful the modelling process and the implementation of the model have been.

Together they influence the overall *acceptability* of the model, which in this case can be considered moderate.

8.3.3 Efficiency

Because of the specific requirements for data collection, the preparations and data collection consumed a lot of effort in the way the model was implemented in this research. From the point of view of model application, some of the effort spent in the 3D motion data collection seems also unnecessary, as the many markers placed on the subject are basically used only to determine the COM location, while all other needed parameters can be obtained from the much fewer markers placed on the poles and skis. In addition, the processing of data in this research was time consuming due to the iterative development of the model taking place alongside.

Despite having provided results of reasonable quality and a somewhat applicable model, the *internal efficiency* of this model implementation can be considered relatively low. It shall, however, be recognised that the measurement and analysis set-up was not designed only with the aim to apply the force application effectiveness model, but also other uses in which, for example, the multiple marker locations are necessary.

In addition, once the model has now been developed, its application can be done with considerable less effort than in this research, provided that sufficient input data can be obtained. The greatest limitations to the application of the model in other studies are probably the availability of the model with regard to data collection and comparable measurement conditions. However, the model, employing quite simple calculations, can be modified with relative ease in order to meet the input data provision. For example, the analysis regarding sensitivity to force measurement methods indicated that the model may be used relatively well with varying force data inputs. The *external efficiency* of the model can thus be considered moderate.

8.4 Conclusions and future insights

The purpose of this research was to develop a model for analysing effectiveness of force application in ski skating for use in cross-country skiing research and coaching. The model, examples of its application, analyses regarding its implementation, and its evaluation are presented above. The main purpose of the research has thus been met. With regard to the specific questions listed in the aims of the study, it can be said that:

1. No indications of usefulness and importance of directed components calculated directly from resultant ski or axial pole forces were identified in this research.
2. Consideration of the translational ski and pole forces, particularly translational resultant and propulsive forces, seems to be an applicable approach to analysing effectiveness of force application in ski skating.
3. Body position, described as the orientation of the line from PFA to COM, is a potentially useful indicator for effectiveness of force application in ski skating.
4. The estimates of translational propulsive ski and pole force, as calculated in this research, seem to be of reasonable order of magnitude, but not very accurate.
5. When considering the translational forces, measurement of ski forces in more than one (vertical) dimension does not seem as important as when considering components calculated directly from the resultant force.
6. Accuracy of the estimates for COM and PFA location are critical when considering translational forces. The orientation of the line from PFA to COM is a major determinant for the magnitude of translational components, i.e. the body position largely determines the translational forces.
7. Due account of pole bending would improve the estimates of pole forces, but the error due to assuming no pole bending is smaller when considering translational forces than for components calculated directly from the axial pole force.

Despite being a pilot study, this research has succeeded in making a meaningful contribution in advancing cross-country skiing research. The developed model may turn out useful also in more practical testing and coaching of cross-country skiers. Certain points regarding implementation and further development of the model in future studies have, however, already been identified.

First of all, variables identified as potentially important in this research should be scrutinized in other studies with bigger data sets in order to test and confirm their possible usefulness. Second, the methods of estimating the ski PFA location shall be explored in order to identify an accurate and reliable solution. Third, it should be considered how to improve the account of pole behaviour during force application, e.g. with better pole marker positioning for motion capture. These three points would probably involve only incremental improvements to the model as described above.

Instead, more profound changes may be required in the model implementation in order to make the data collection and processing more effective, while at the same time providing sufficient numbers of push-offs from both sides for analysis. Potential solutions include such as reducing the number of markers needed for motion capture and designing the measurement set-up for roller-ski skating on a treadmill. However, for on-snow solutions also non-marker solutions for motion data shall be considered.

Eventually, when the methods of data collection and processing have been sufficiently streamlined, the aim should be to integrate the data collection and analysis into a single system offering a one-stop-shop for force effectiveness analysis. The integration could extend also to collection and processing of other signals from e.g. EMG, heart rate, and exhaust gas measurements. For the needs of coaching and exercise testing, such a system shall be made easy and quick to use in order to enable provision of analysis result feedback without remarkable delays.

Alongside this development, also opportunities in other contexts should be explored. For example, the analysis of other sports and physical exercises involving somewhat comparable movements, e.g. classical cross country skiing, ice and roller skating, and running, could be potential application contexts.

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