Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

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Energetic cost of double poling and diagonal stride in classical cross-country skiing at different speed-slope combinations: A literature review

Bachelor's thesis in Human Movement Science
Supervisor: Mireille Van Beekvelt
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Abstract

The purpose of this literature review is: 1) to provide an overview of which classical cross-country skiing sub-technique (double poling (DP), diagonal stride (DS)) yields the most beneficial energetic cost (EC), i.e., low energy cost and high gross efficiency at different speed-slope combinations; and 2) if the athletes' choice of sub-technique (DP, DS) agrees with the goal of using the sub-technique that yields the most beneficial EC accordingly. **Methods:** The literature search was conducted using the databases SPORTDiscus and Google scholar. The primary articles included trials on DP and DS in relation to EC, as well as trials investigating athletes' free choice of sub-technique, both at different speed-slope combinations. **Results:** The main findings were that: 1) DS has a more beneficial EC at a low speed-high slope combination, and DP at high speed-low slope combination; 2) the athletes' free choice of sub-technique corresponds with the goal of obtaining a beneficial EC. **Conclusion:** When considering EC, there seems to be a "cheapest" sub-technique (DP, DS) for different terrains in classical cross-country skiing. Also, athletes' free choice of sub-technique seems to be in accordance with obtaining the "cheapest" sub-technique. It also seems that choice and change of sub-technique occurs due to other determinants related to EC.

Abstrakt

Formålet med denne litteraturstudien er å: 1) skaffe en oversikt over hvilke under-teknikker i klassisk langrenn (staking, diagonalgang) som gir mest fordelaktig "energetic cost" (EC), dvs. lave energikostnader og høy bruttoeffektivitet (GE) ved forskjellige hastigheter og stigninger; og 2) om utøvernes valg av under-teknikk stemmer overens med den teknikken som har mest fordelaktig EC. **Metode:** Litteratursøket ble utført ved hjelp av databasene SPORTDisucus og Google scholar. Primærartiklene inkluderer studier som undersøker staking og diagonalgang i forhold til EC, samt studier som ser på valg av under-teknikker ved ulike hastigheter og stigninger når utøverne står fritt til å velge teknikk selv. **Resultat:** Hovedfunnene var: 1) diagonalgang har mer fordelaktig EC på lav hastighet - høy stigning, mens staking har en mer fordelaktig EC på høy hastighet - lav stigning; 2) Ved fritt valg ser det ut til at utøvernes valg av under-teknikk samsvarer med den mest fordelaktige EC. **Konklusjon:** Det ser ut til å være en under-teknikk (staking, diagonalgang) i klassisk langrenn som er mer fordelaktig på ulike hastigheter og stigninger. Utøvernes foretrukne under-teknikk på forskjellige hastigheter og stigninger ser også ut til å samsvare med å oppnå en fordelaktig EC. I tillegg ser det ut til at valg og endring av under-teknikk også påvirkes av andre faktorer relatert til EC.

1. Introduction

Cross-country skiing (XC-skiing) is considered as one of the most demanding endurance sports as it consists of whole-body movements at different intensities, techniques, and durations (Sandbakk et al., 2016). In XC-skiing there are two main techniques, freestyle-, and classical technique. Both have several sub-techniques that work as gears, which are applied on different terrains according to speed and slope (Losnegard, 2019; Løkkeborg & Ettema, 2020; Pellegrini et al., 2013). In classical XC-skiing, the sub-techniques that have been studied most frequently are double poling (DP), and diagonal stride (DS) (Björklund et al., 2015). DS is executed by exerting force through the skis and poles in a coordinated pattern that resembles walking and running, since the push of one arm is performed at the same time as the push of the contralateral leg (Pellegrini et al., 2013). DP is executed with symmetrical actions in both poles and the legs, where the propulsive actions are performed with a trunk flexion where most of the force is exerted from the arms through the poles (Holmberg et al., 2005). Nevertheless, it has been shown that the optimal force transfers to the ground via the poles might not be attained by the arms, shoulders, and trunk muscles alone, but also by active movement of the legs (Holmberg et al., 2005). Although the upper body plays a critical role in DP, the arms and legs contribute about equally to whole body oxygen uptake (Calbet et al., 2004; Rud et al., 2014). On the contrary, during DS, the arms and legs contribution to the whole-body oxygen uptake are about 30% and 70% respectively (Calbet et al., 2004)

Thus, the two sub-techniques (DP, DS) are characterized by different contributions from upper and lower limbs (Pellegrini et al., 2013). It is known that DS often is performed on low speeds and steeper slopes, and DP are often performed at high speeds and lower slopes (Løkkeborg & Ettema, 2020), and that XC-skiing has unlike most other endurance sports larger variations of speeds and slopes during a competition. Approximately 50%, 35%, and 15%, of total race time is spent on uphill, flat, and downhill, respectively. Due to constantly changing terrain during a XC-skiing race, a skier must master the ability to effectively use different sub-techniques (Losnegard, 2019), which will have positive implications for locomotion efficiency and performance during competition (Pellegrini et al., 2013).

1.1 Energetic cost in XC-skiing

A lot of research has been done on which sub-technique in classical XC-skiing that seems to be the “cheapest”, meaning the most beneficial considering energy cost and gross efficiency, on different speeds and slopes (Andersson et al., 2017, 2021; Carlsson et al., 2021; Dahl et al., 2017; Pellegrini et al., 2013). Despite this, as far as we know there is no literature overview on this topic, as well as the athletes' free choice of sub-technique. In order to provide such a literature review, we use energetic cost (EC) as a collective term for measures that are used in the literature; energy cost or economy ($J \cdot Kg^{-1} \cdot m^{-1}$), and gross efficiency (GE; %). Hereunder, a low energy cost and a high GE is considered as a beneficial EC. Throughout this paper, "energy cost or economy" will be referred to as "energy cost".

In this review, EC was used to evaluate which sub-technique is the most beneficial at a given speed-slope combination, and if this corresponds with the athletes' own free choice of sub-technique. It is suggested that the overall purpose of choosing or changing sub-technique is to minimize the energy cost of movement, obtained by an energy-efficient movement pattern (Carlsson et al., 2021). Hence, it is important to apply the "cheapest" sub-technique at different speed-slope combinations as the ability to efficiently use metabolic energy to produce work is considered a key factor for performance (Grasaas et al., 2014; Losnegard, 2019). It is therefore likely to consider the EC of movement in XC-skiing as a key determinant for where a sub-technique is most beneficial, but also as a determinant for changing sub-technique when the terrain changes. In addition, there is a consensus that EC is a main determinant for choosing either DP or DS at different speed-slope combinations. Based on earlier research it seems that there is a crossover in energy cost between DP and DS at 3—4º indicating DP to be more beneficial than DS at slopes <3—4º, and DS to be more beneficial than DP at slopes >3—4° (Andersson et al., 2017; Dahl et al., 2017; Pellegrini et al., 2013). In addition, Andersson et al. (2021) found DS to have a lower energy cost and a higher GE than DP at a fixed slope of 5° at 5-8 $km \cdot h^{-1}$. This is also why we chose to define low- and high slopes, below and above 4°. Even if a speed-slope combination may exist where DP and DS are respectively more beneficial considering EC, it is still not certain if athletes use these sub-techniques accordingly.

1.2 Choice of technique in relation with EC

It has been suggested, as mentioned, that the ability to make energy-efficient sub-technique-transitions is an important factor for XC-skiing performance (Losnegard, 2019). Therefore, it is natural to suggest that the athletes change and choose sub-technique at different speeds and slopes to use the technique with the most beneficial EC. However, it is unlikely that this is the determinant responsible for the choice and change of sub-technique by itself. Change of sub-technique in classical XC-skiing can be defined as a gait-transition, and there has been done extensive research on what determines gait transitions between e.g., walking and running (Hoyt & Taylor, 1981; Kung et al., 2018; Mercier et al., 1994). According to Hoyt and Taylor (1981) the overall goal of gait transitions and choice of locomotion mode is to reduce the energy cost of the movement. Thus, it can be suggested that the purpose of changing sub-technique in classical XC-skiing is to minimize the energy cost of movement, and thus provide a more beneficial EC. However, several studies have suggested that the choice and change of sub-technique on different speed-slope combinations do not only occur in order to minimize the energy cost and/or obtain a high GE (Andersson et al., 2017, 2021; Dahl et al., 2017; Pellegrini et al., 2013). The literature suggests that a beneficial sub-technique regarding EC exists at a certain speed-slope combination. Even though the athletes may choose sub-technique in order to obtain a beneficial EC, this still raises the question if they change and choose sub-technique due to other determinants that may relate to EC.

1.3 Other possible determinants for choice of sub-technique

Some findings indicate that EC may not be a determinant by itself for the choice of either DP or DS at different speeds and slopes, but that the choice may relate to other determinants related to EC (Andersson et al., 2017; Dahl et al., 2017; Pellegrini et al., 2013). Elite skiers may change sub-technique in order to lower the mechanical demands of the movement by increasing the ability of utilizing the body´s mechanical energy (Dahl et al., 2017; Løkkeborg & Ettema, 2020). This is similar to other locomotion modes, e.g., walking and running (Farley & Ferris, 1998; Kung et al., 2018). Previous research has suggested different determinants for choice of sub-technique in classical XC-skiing such as: leg thrust-time, optimized oxygen utilization, pole forces, power fluctuations and propulsive actions (Andersson et al., 2021; Björklund et al., 2015; Dahl et al., 2017; Pellegrini et al., 2013). Therefore, the current review will discuss if the choice of sub-technique by athletes occurs due to other determinants that may relate to obtaining a beneficial EC.

1.4 Main aim of this review

The main purpose of this review was to investigate the current available literature in order to: 1) gain an overview of which classical XC-skiing sub-technique (DP, DS) yields the most beneficial EC at different speed-slope combinations; and 2) investigate if the athletes' choice of sub-technique (DP, DS) agrees with the goal of using the sub-technique that yields the most beneficial EC. In addition, this literature review will also discuss other potential determinants related to EC that affect the choice and change of sub-technique in classical XC-skiing.

2. Methods

2.1 Search strategy

The search for this literature review was conducted using the databases SPORTDiscus and Google scholar. The search took place in week 4 to 7 2023. The following keywords were used in the general search strategy: (“Cross country skiing techniques” OR ”cross country skiing“ OR ”XC skiing“ OR “Nordic skiing“ OR “different locomotion modes cross country skiing”) AND (“incline“ OR “slope”) AND (”speed”) AND (”energy cost“ OR ”metabolic rate“ OR ”metabolic cost” OR “gross efficiency” OR “energy cost in sports” OR “energy cost of gait-transitions” OR “energy cost cross-country skiing” OR “metabolic rate cross country skiing” OR “metabolic energy cost cross country skiing” OR “gross efficiency cross country skiing” OR “energy cost of double poling and diagonal stride”) AND (”kinematics“ OR ”mechanical energetics”).

2.2 Inclusion and exclusion criteria

The search gave an initial result of 67 articles. They were then checked for the following inclusion criteria: 1) had to be written in English; 2) had to be a peer-reviewed journal article; 3) had to have trials conducted on humans; 4) had to be executing trials of classical roller skiing on motor-driven treadmills or snow-skiing; 5) involve studies investigating trials on both DP and DS in relation to energy cost and/or gross efficiency and/or metabolic rate and/or metabolic cost and/or metabolic energy cost; 6) additionally studies that involved investigation of the athletes’ free choice of sub-technique (DP and DS) in classical XC-skiing was included. At least two authors of this review read the title and abstract of the initial 67 articles, and 7 articles were finally selected as primary articles.

3. **Results**

3.1 Primary findings

In general, table 1 shows a summary of relevant aspects of the primary articles such as: at which studies EC was considered and investigated; number of subjects in each study; gender; body weight; age; and body height of the subjects. The tests from the collected literature were done with different outcome-variables as measures of energetic cost as shown in the "EC" column in the table. Table 1 also shows which speed-slope combinations were used in each study protocol. All tests were done such that steady state could be obtained, and all speed-slope combinations were held for at least 3 minutes. All references had a submaximal protocol, except Carlsson et al. (2021) and Pellegrini et al. (2013) that did not mention intensity level. The numbered references in table 1 e.g., (1) Andersson et al. (2017), correspond to the numbered references in table 2. This was done in order to make it easier for the reader to compare the results from table 2 in relation with the study-characteristics in table 1.

Table 1: Characteristics from the seven studies included from the literature search.

Study	***n***	**Age (yr.)**	**BW (kg)**	**Height (cm)**	**Study design**	**EC**
(1) Andersson et al. (2017)	M 11	24.3 ± 3.6	78.7 ± 5.9	182.1 ± 5.1	Rollerski on treadmill Speed-slope combinations: - 9 different slopes (0-8°) at 16.0 $km \cdot h^{-1}$ (DP) and 9.5 $km \cdot h^{-1}$ (DS)	Energy cost or economy ($J \cdot Kg^{-1} \cdot m^{-1}$)
(2) Andersson et al. (2021)	M 12 F 11	M 18.2 ± 1.0 F 18.2 ± 1.2	M 74.3 ± 6.6 F 63.5 ± 6.9	M 180.8 ± 6.0 F 169.8 ± 5.0	Rollerski on treadmill Speed-slope combinations: - 5º slope at 5, 6, 7 or 8 $km \cdot h^{-1}$ (DP, DS)	Energy cost or economy ($J \cdot Kg^{-1} \cdot m^{-1}$) Gross efficiency (%)
(3) Carlsson et al. (2021)	M 15	22.0 ± 4.0	79.0 ± 9.9	183.0 ± 9.0	Rollerski on treadmill Speed-slope combinations: - 2.5° slope and 13 $km \cdot h^{-1}$ (DP, DS)	Gross efficiency (%)
(4) Dahl et al. (2017)	M 15	24.0 ± 2.7	76.4 ± 6.4	182.6 ± 4.6	Rollerski on treadmill Speed-slope combinations: - 2.9° slope at 12.5 $km \cdot h^{-1}$ (DP), and 6.8° slope at 6.5 $km \cdot h^{-1}$ (DS).	Gross efficiency (%)

(5) Ettema et al. (2017)	M 8	22.4 ± 1.7	80.3 ± 7.7	183.7 ± 4.4	Rollerski on treadmill Speed-slope combinations: - 1.72° to 6.28° slope at approximately 20 km·h^{-1} to 6-7 km·h^{-1} with free choice of sub-technique (DP, DPK or DS)	- NA
(6) Løkkeborg & Ettema (2020)	M 12 F 9	M 21.2 ± 4.0 F 20.4 ± 2.1	M 72.4 ± 4.7 F 65.0 ± 6.6	M 179.6 ± 5.9 F 171.6 ± 4.3	Rollerski on treadmill Speed-slope combinations: - 3 slopes (5°, 7°, 9°) at 7, 8 and 10 km·h^{-1} with free choice of sub-technique (DP, DPK or DS)	- NA
(7) Pellegrini et al. (2013)	M 15	30.7 ± 5.3	72.0 ± 4.7	178.0 ± 0.05	Rollerski on treadmill Speed-slope combinations: - 8 slopes (0-7º) at 10 km·h^{-1} speed (DP, DS). - 6 speeds (6-18 km·h^{-1}) at 2° slope (DP, DS).	Energy cost or economy (J·Kg^{-1}·m^{-1})

DP = double poling, DS = diagonal stride, DPK = double poling with kick, M = Male, F = Female, yr. = years old, BW = body weight, H = body height, *n* = number of subjects, NA = data not available, EC = Measurement for energetic cost. Age, body weight, and body height are presented as mean ± SD

Table 2 shows which sub-technique has the most beneficial EC at different speed-slope combinations. The color-coded results (DP in red, DS in light blue) show the athletes' free choice of sub-technique at different speed-slope combinations. The bottom left quadrant with gray shade represents low speed-high slope (<10 km·h^{-1} and >4°) and the upper right quadrant with gray shade represents high speed-low slope (>10 km·h^{-1} and <4°).

Table 2: Most beneficial sub-technique at the different speed-slope combinations between DP and DS, and the athletes´ preference of either DP or DS at different speed-slope combinations.

Speed → ($km \cdot h^{-1}$) Slope (°) ↓	5	6	7	8	9	10	11	12	13	14	15	16	17
0						DP (7) DP (7)						DP* (1)	
1						DP* (7) DP (7)						DP* (1)	
2		DS (7) DP (7)	DP (7)	DP (7) DP (7)	DP (7)	DP (7) DP (5) (7)	DP (5) (7)	DP (7) DP (5) (7)	DP (5) (7)	DP (7) DP (7)	DP (7)	DP* (1) DP (7)	DP (7)
3						DP (6)	DP (6)	DP (6)	DP* (3) (4) DP** (4)			DP* (1)	
4				DS (6)		DS (7)							
5	DS* (2)	DS* (2)	DS* (2) DS (5)	DS* (2) DS (5) (6)	DS (5) (6)	DS (7)							
6						DS (5) (7)							
7			DS* (4) DS** (4)			DS (7)							

1 = Andersson et al. (2017), 2 = Andersson et al. (2021), 3 = Carlsson et al. (2021), 4 = Dahl et al. (2017), 5 = Ettema et al. (2017), 6 = Løkkeborg & Ettema (2020), 7 = Pellegrini et al. (2013). DP = double poling, DS = diagonal stride. Text in black is obtained from the studies investigating EC, and indicate a more beneficial sub-technique at that speed-slope combination. * (*P<0.05*) and ** (*P<0.01*) indicates a significant beneficial difference between DP and DS. All color-coded results in red (DP) and light blue (DS) shows the athletes' preference and free choice of sub-technique at a given speed-slope combination. DP and DS with * (*P<0.05*) and ** (*P<0.01*) in color means a significant preference of that sub-technique by the athletes

The main findings of this literature review are that DS has a more beneficial EC at a low speed-high slope combination, and DP has a more beneficial EC at a high speed-low slope combination (table 2). In between these "extremities" a gradual transition between DP and DS can be seen, and an imagined horizontal line at 4° in table 2 visualizes this. It also seems that the athletes' free choice of sub-technique (red and light-blue results in table 2) corresponds with the goal of obtaining a beneficial EC (black results in table 2).

4. Discussion

The main findings of this literature review are that DS was found to be a more beneficial sub-technique considering EC at low speed-high slope combination, and DP at high speed-low slope combination (table 2). Athletes' free choice of sub-technique also seems in accordance with obtaining a beneficial EC (table 2).

4.1 The most EC beneficial sub-technique at different speed-slope combinations

The findings of this review are, as mentioned, that there is a difference in EC between DP and DS on different speed-slope combinations (table 2). Among the literature collected, Andersson et al. (2017), Carlsson et al. (2021), Dahl et al. (2017), and Pellegrini et al. (2013) found DP yielding the most beneficial EC on high speed-low slope, and Andersson et al. (2021), and Dahl et al. (2017) found DS yielding the most beneficial EC on low speed-high slope (table 2). In addition, the relevant papers show a tendency of a crossover in energy cost, and GE between DP and DS at around 3—4°. This indicates DP to be "cheaper" than DS at slopes <3—4° (Andersson et al., 2017; Dahl et al., 2017; Pellegrini et al., 2013), and DS to be "cheaper" than DP at slopes >3—4° (Andersson et al., 2021; Dahl et al., 2017). Andersson et al. (2021) also found a decreasing energy cost and increasing GE for DP at increasing speeds, and vice versa for DS at increasing slopes. Therefore, the results in this review can be seen as highly consistent and in agreement with the idea that there is a beneficial technique at different speed-slope combinations (table 2).

4.2 Athletes' free choice of sub-technique

As shown in the results in table 2, the athlete's free choice of sub-technique seems in accordance with obtaining a beneficial EC. This means that the athletes are in fact utilizing the most beneficial sub-technique at different speed-slope combinations. As mentioned in connection with table 2, an imagined horizontal line at 4° illustrates that DP occurs on low slopes, and DS on high slope, regardless of speed. This suggests that changes in slope are a factor that could determine the choice of sub-technique. This could be seen in line with the findings of Ettema et al. (2017) and Pellegrini et al. (2013) where slope rather than speed seemed to steer the choice of sub-technique. The reason for slope being a steering parameter for choice of sub-technique could be explained by the gravitational component of increasing slopes that requires the athlete to reposition their body in preparation for the next pole plant (Ettema et al., 2017; Stöggl & Holmberg, 2016). It is therefore suggested that small differences in joint angles of the limbs in the lower-extremities may exist depending on slope, and in turn affect the energy consumption of the athlete (Ettema et al., 2017; Stöggl & Holmberg, 2016). This may explain the athletes' choice of DS at steeper slopes (table 2) as DP becomes relatively more energy consuming with increasing slopes.

With that being said, it is conceivable that the athlete's choice of sub-technique occurs due to obtaining the most beneficial EC (table 2), which is influenced by slope rather than speed as slope may affect the energy consumption of the athlete the most of those two (Ettema et al., 2017; Stöggl & Holmberg, 2016). This can somehow be expected as it has been suggested that the overall purpose of changing sub-technique is to minimize the energy cost of a movement by obtaining the most energy-efficient movement pattern (Carlsson et al., 2021; Grasaas et al., 2014). Løkkeborg and Ettema (2020) also found slope rather than speed to be the main steering parameter for athletes' choice of sub-technique. They also mention that most of the athletes chose sub-technique on a specific speed-slope combination (Løkkeborg & Ettema, 2020), as table 2 also shows. This may occur in order to obtain an energy-efficient movement pattern (Carlsson et al., 2021). The findings here as well are highly consistent and seem to be in agreement with the athletes choosing a movement solution that provides the most beneficial EC (table 2).

4.3 Possible determinants relating to EC for choice of sub-technique

The findings from the collected literature suggests that athletes choose the "cheapest" sub-technique considering EC at the given speed-slope combinations (table 2). The literature also suggests that in classical XC-skiing, EC plays a major role in choice of sub-technique (table 2). Still, the actual determinants of changing sub-technique in changing terrain may not be EC itself, but other determinants closely related to EC (Andersson et al., 2021; Björklund et al., 2015; Dahl et al., 2017; Pellegrini et al., 2013). DP is suggested to be a more beneficial sub-technique than DS at high speed-low slope (table 2). At higher speeds and lower slopes larger power fluctuations are observed for DS than for DP. This could be explained by the fact that the lower-extremities are impaired to a far larger extent during DS-action than DP at higher speeds (Dahl et al., 2017; Pellegrini et al., 2013). Since, for DP at higher speeds, the lower-extremities are less impaired, as a more active use of the lower-extremities increases the amount of energy stored in the body during the recovery phase of propulsion, and is "reutilized" during the next propulsive action. This may provide a more beneficial EC by using DP rather than DS at higher speeds and lower slopes, e.g., 12.5 $km \cdot h^{-1}$ and 2.9° (Dahl et al., 2017). This could be seen in line with findings of Carlsson et al. (2021) as it shows significantly higher GE for DP than DS at 3° (table 2). When utilizing DP at higher speeds and lower slopes, the lower limbs are impaired to a much lesser extent as DP allows a lower physiological response indicated by lower heart rate and respiratory exchange ratio (Dahl et al., 2017). Therefore, utilizing DP at high speed-low slope may be more beneficial than utilizing DS. Thus, utilizing the sub-technique with lower power fluctuations could determine the athletes' choice of sub-technique along with EC.

On the other hand, Dahl et al. (2017) found these power fluctuations to be much less apparent for DS than DP at low speed-high slope. This may be explained by the fact that the lower extremities have a smaller time-slot to move (increasing the thrust-time) at high skiing speed (Dahl et al., 2017). By matching the skiing speed, the power fluctuations are minimized, and DS may therefore be more beneficial as the GE is found to be higher for DS than DP at increasing slopes (Dahl et al., 2017). The higher GE and lower physiological response for DS at steeper slopes can be indicated by lower respiratory exchange ratio and lactate values according to Dahl et al. (2017). In addition, the preference of DS over DP at steeper slopes may be caused by a reduced ability, during DP-action, to "reutilize" the body's stored energy as the lower-extremities are impaired to a larger extent. Therefore, this can increase the demands of force generation through the upper-body during DP-actions at steeper slopes, and may cause muscle-fatigue in the upper-body. Therefore, minimizing power fluctuations could contribute to the differences in EC between DP and DS at different speed-slope combinations, as well as influence the athletes' preference of sub-technique.

Another possible determinant that should be taken into consideration is leg thrust-time (LTT). LTT can be defined as the "time of application of the force exerted by the legs" (Pellegrini et al., pp. 1426). Despite that LTT is only relevant for DS of the sub-techniques we investigated, it may still be considered as a determinant for the choice of sub-technique. Pellegrini et al. (2013) found a decrease in LTT for increasing speeds, and an increase in LTT for increasing slopes. This fits with the notion that DP is favored on high speed-low slope, and DS on low speed-high slope (table 2). It has earlier been suggested that 0.10 seconds of LTT is too short to allow the lower-extremity muscles to reach their maximal force generation, and that the time required to generate maximal muscle forces in the lower-extremities is more than twice this time (Harridge et al., 1996). Therefore, Pellegrini et al. (2013) hypothesized that an LTT of >0.22 seconds (approximately twice of 0.10 seconds) is optimal for maximal force generation through the lower-extremities during DS-action. It was also shown by Pellegrini et al. (2013) that the change from DP to DS at 3—4° occurs where an LTT of >0.22 seconds is observed. This may allow a longer time for force exertion and may therefore lower the cost of muscle force generation (Bellizzi et al., 1998). LTT could therefore relate to EC as a determinant for sub-technique selection as Pellegrini et al. (2013) found a crossover in energy cost between DP and DS at 3—4°. This is in accordance with the athletes' change from DP to DS at 3—4° where an optimal LTT of >0.22 seconds for DS-action is observed. Also, Dahl et al. (2017) suggested that at a slope of 2.9°, the skiing speed is too fast to allow optimal LTT during DS-action as this impairs the generation of maximal muscle force in the lower-extremities, and in extension of that, the ability to move at high skiing speed. Therefore, DS might be favored at steeper slopes (Pellegrini et al., 2013).

Dahl et al. (2017) also indicated that the ability to remain below a limit of pole forces could act as a determinant for the change from DP to DS at increasing slopes in order to minimize the mechanical demands of the movement, and reduce the risk of upper body muscle fatigue. Remaining below a limit of pole forces may act as a determinant for choosing DS rather than DP at steeper slopes, as DS activates the under-extremities to a larger extent, and thus reduces the amount of pole forces that is required through the upper body (Dahl et al., 2017). This will therefore increase the effectiveness of propulsive actions and decrease the mechanical demands of movement by utilizing DS rather than DP. During DP-action at steeper slopes, the lower-extremities are impaired to a larger extent than during DS-action (Dahl et al., 2017). This increases the demands of muscle force generation through the upper body, and may result in the athlete exceeding the limit of pole forces and may lead to an upper body muscle fatigue. Pellegrini et al. (2013) also suggested that change from DP to DS at increasing slopes could be explained by a limit of pole forces and that there is a limit in the force an athlete would like to exert when changing sub-technique. This limit can be explained as a threshold, and when exceeding this threshold the athlete would change from DP to DS to reduce the stress applied to the musculoskeletal system, and thus avoid upper-body muscle fatigue

(Pellegrini et al., 2013). Therefore, the ability to remain below a threshold for pole forces may explain why DP is abandoned in favor of DS by athletes at steeper slopes.

Another possible determinant for choice of DS rather than DP at low speed-high slope could be due to better oxygen utilization and blood flow during DS-action at steeper slopes (Björklund et al., 2015). A better oxygen utilization will lead to lower reliance on the type II-muscle fibers for force production (Van Hall, 2000), which may cause a more beneficial EC as the lactate production decreases and leads to a more energy-efficient movement pattern (Carlsson et al., 2021). Utilizing DP at steeper slopes may cause irregular blood flow (Andersson et al., 2021), increase the mechanical demands of movement in the upper-body extremities, and cause an impaired oxygen utilization (Calbet et al., 2005; Carlsson et al., 2021). This can be seen in the coherence of larger power fluctuations during DP-action at steeper slopes, as this may lead to greater demands on the upper-body due to the fact that impairments are larger for DP than DS at steeper slopes (Dahl et al., 2017).
Thus, the athletes may use DS in favor of DP at low speed-high slope in order to maintain a high GE, low energy cost, an efficient oxygen utilization, reduce mechanical hindrance, and avoid upper-body muscle fatigue (Andersson et al., 2021; Björklund et al., 2015; Dahl et al., 2017; Pellegrini et al., 2013).

4.4 Methodological considerations

The literature collected in this review has used different protocols, and measures of outcome where age and gender also differ (table 1). This may affect the interpretations of the findings as the relevant papers have different approaches and different participant compositions. In order to simplify the interpretation of the findings, all the studies should ideally have been conducted with the same study designs, and measurements. Despite different protocols, study designs, participants, and anthropometrics (table 1) the findings in the literature seem to be consistent, and therefore, one may conclude that the results are generalizable. Still, although this current review only investigates DP and DS, the studies of Ettema et al. (2017), Løkkeborg and Ettema (2020), and Pellegrini et al. (2013) have also investigated double poling with kick. This may affect the picture of where DS and DP yields the most beneficial EC, and the athletes' free choice of sub-technique as it may create a "gap" in the trials where neither DP nor DS is used.

Another possible issue that has to be taken into consideration is the fact that Andersson et al. (2021) have done trials on both males and females (table 1). In Andersson et al. (2021), the females had a higher energy cost than males during DP-action. This is probably due to a more developed upper-extremity strength for the males resulting in a better skiing-economy (Andersson et al., 2021). The trials in Andersson et al. (2021) are also conducted on junior-skiers where the same issue may apply as junior-skiers often have a less developed upper-extremity musculature than senior skiers. This may explain the higher energy cost for DP compared to DS at 5° from Andersson et al. (2021). This is in line with Andersson et al. (2017), Carlsson et al. (2021) and Pellegrini et al. (2013), all finding DS to have a more beneficial EC than DP at slopes steeper than 3—4°. Therefore, despite some differences in absolute energy cost compared to other studies, the study of Andersson et al. (2021) was considered relevant and thus included.

5. Conclusion

There is a tendency in all 7 papers that DP provides the most beneficial EC at high speed-low slope, and DS the most beneficial at low speed-high slope. When athletes are given free choice of sub-technique at different speed-slope combinations, there is also a tendency that they prefer the sub-technique with the most beneficial EC. Thus, the athletes' free choice of sub-technique seems to be in line with findings of which sub-technique obtains the "cheapest" given EC at different speeds and slopes. Despite this, it seems that possible determinants of sub-technique selection may also be much related to LTT, power fluctuations, propulsive actions, and pole forces, which in turn may affect the mechanical demands of locomotion.

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