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Analysis of the pushing phase in Paralympic cross-country sit-skiers – Class LW10

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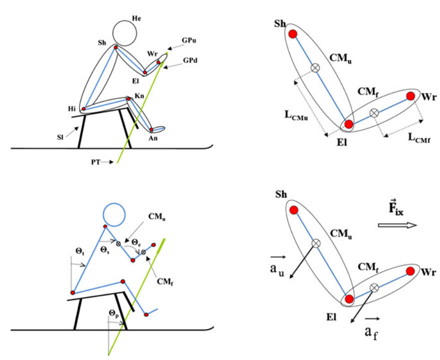
GRAPHICAL ABSTRACT



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ABSTRACT

Paralympic Cross-Country sit-skiers use adaptive equipment, with a resulting gesture similar to double poling techniques adopted by able-bodied skiers. Despite the similarity, a specific attention on the gesture performed by sit-skiers is needed. The paper focuses on the sledge kinematic and on inertia effect of upper body motion which is translated in a propulsive effect in the early stage of the pushing cycle. In particular a group of 7 elite sit skiers of class LW10 were recorded with a video-based markerless motion capture technique during 1 km sprint Paralympic race. A

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biomechanical model, consisting of 7 anatomical points and 4 technical ones, is used to track the kinematics from video-images, then body segments, joints of interest and relative angles are evaluated. In this paper we focus on the biomechanics of the poling cycle, in particular prior to the onset of pole plant. The aim was to evaluate the contribution of the upper body to the early stage of the propulsive action. To this porpoise body inertial forces for each athlete are calculated using kinematic data, then normalized with respect to the athlete's body mass. The results show that in LW10 sit-skiers an important sledge propulsion, prior to the onset of pole plant, is provided by the inertial effect, due to the upper body region (arms and forearms) motion.

Introduction

An increasing number of people with disabilities are involved in adaptive sports, ranging from local community recreation event to elite Paralympic games. Physical activity is indeed seen as a mean to both preserve residual motor functions and prevent further complications. In such a way, playing sport is also a great opportunity for an excellent social reintegration, parallel to positive effects on self-efficacy, psychological recovery, health, independence and overall well-being. The number of adaptive outdoor sports played by disabled athletes has widely enlarged during the last two decades, surely considering global advances of assisting technology and personal training in obtaining better performances. Adaptive sports can be competitive or recreational and usually they are similar to typical sport activities. However, modifications for people with disabilities to participate are necessary, both in rules and in equipment.

Among Paralympic winter sports, the Cross-Country (XC) sit-skiing is one of the adaptive discipline also thought for athletes who have to use sit-ski equipment (Fig. 1), due to impairments affecting lower limbs (e.g. amputations, muscular dystrophy, cerebral palsy, brain or spinal cord injuries, etc.). XC sit-skiing was performed for the first time in 1976 during the opening exhibition at the Winter Games in Örnsköldsvik, Sweden, although it was only introduced as a Paralympic discipline in 1988 in Innsbruck, Austria.

Sitting XC-athletes, as reported in the International Paralympic Committee Classification Rules and Regulations-Cross-Country Skiing and Biathlon handbook [1], are divided into five classes according to the level of impairment and activity limitations [2,3]. Classes are named LW10, LW10.5, LW11, LW11.5 and LW12, where LW is the acronym of locomotor winter. LW12, which is the highest one, corresponds to a complete trunk control capacity. On the contrary LW10 is the lowest one and corresponds to the absence of functional trunk control ability. A percentage system, based on the classes, is used to determine all the athlete adjusted finishing time. In this paper authors will specifically focus on the LW10 class.

Fig. 1 Cross-country sit-skiers.

XC sit-skiing is characterized from both an adaptive equipment and a proper sporting gesture used to perform propulsion. The first consists of a suitable sitting position, made of a sledge mounted on a pair of traditional classic skis on the bottom side, while propulsion is achieved exploiting shoulders, arms and eventually trunk muscles by pushing symmetrically on two hand-held poles. Considering specifically LW10 athletes, they have a sitting position in which the knees are higher than the hip [4]. This sitting position and the backrest of the sledge, allow only small antero-posterior of the trunk respect to the upright position. As matter of fact, since these athletes have no control of abdominal or dorsal muscles, only small trunk range of motion can be compensated with other residual functions. Greater trunk range of motion would result in a fall of the trunk that cannot be controlled by the skier.

The resulting pushing technique performed by XC sit-skiers is similar to double poling (DP) adopted by standing able-bodied XC-skiers [5], in which the athlete pushes simultaneously with the two poles. DP is well studied for able-bodied skiers: information on joints movements of both upper and lower limbs was provided by different authors [6–8] In particular Smith et al. [8] performed a 2D kinematic analysis to detect the position of the shoulder and the centre of mass during an Olympic race and Stöggl and Holmberg presented an integrated study of the 3D kinematics and kinetics of the DP gesture. Holmberg et al. [7] carried out studies regarding elite able-bodied skiers with locked knees and ankles, to show the legs contribution in increasing poling force.

Although indicative, these results cannot be extended to sit-skiers because of the different posture and the inability to activate some muscles [9]. Besides in sit-skiers the faculty of recruiting or not abdominal muscles strongly influences both pushing techniques and exerted forces. Thus, it is necessary to focus specifically on gestures performed by disable athletes to point out the cycle biomechanics. Unfortunately, only few studies are related to the kinematics of XC sit-skiers; in particular Bernardi et al. [10] and Gastaldi et al. [11] are cross-sectional studies conducted during Winter Paralympic Games, respectively in Torino 2006 and Vancouver 2010. Rapp et al.

[4] performed laboratory tests to assess the muscle activation according to the different sitting position and Rosso et al. study [12] the trunk range of motion and trunk flexion was inquired. Bernardi et al. [10] demonstrated the fatigue effect by a consistent speed decrease throughout the performance during the 15 km race and changes also in cycle parameters. In Gastaldi et al. [11], in order to check on the field the gesture of different elite skiers, a markerless motion capture technique was used to collect kinematics. Results show that a typical cycle consists of 3 main phases: poling (PP), transition (TP) and recovery (RP), as depicted in Fig. 2A. The PP is the phase in which the sledge accelerates, in TP the gesture of the push is finalized and then in the RP the athlete gets ready for a new cycle. The PP starts with the maximum wrist elevation respect to the ground and ends when the sledge reaches its maximum velocity, TP starts with the conclusion of the PP and it ends with maximum elbow extension and finally the RP starts with the conclusion of the TP and it ends with the beginning of the PP of the following cycle.

Trends of sledge velocity and poles angle of a typical cycle [11] are reported respectively in Fig. 2B and C. The solid line reproduces the part of the cycle in which poles are both in contact with the ground, respect to the remaining cycle represented with a dotted line. Focusing on the sledge velocity, a meaningful positive acceleration can be observed during the PP, prior the pole planting. This propulsive force is particularly important when considering LW10 athletes. As a matter of fact higher class at pole plant have a higher pole angle with respect the vertical, thanks to the trunk flexion. This resulting in a more effective push. On the contrary lower class cannot lean forward with the trunk so the pole angle at pole plant is lower. This propulsive force partially compensates this disadvantage and is important for the effectiveness of PP.

Since LW10 athletes have no functional abdominals or extensors and no buttock sensibility, the hypothesis is that the propulsive force is associated to the inertial effect due to the abrupt lowering of both arms and the trunk swing, which

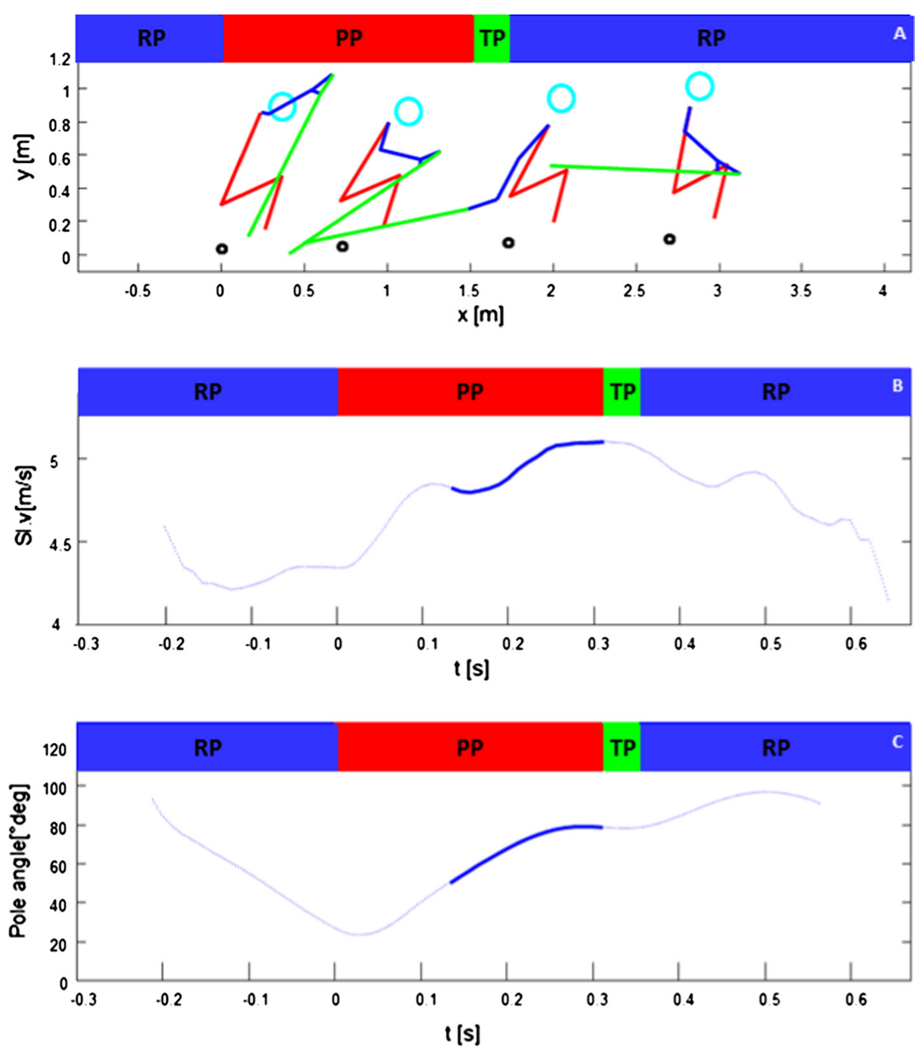

Fig. 2 Pushing poling gesture (PPG) for XC sit-skiers, consisted of 3 main phases: poling (PP), transition (TP) and recovery (RP). Four main observed actions are reported with stick diagrams obtained with respect to the world reference frame: maximum wrist elevation with respect to the ground (coincident with $t = 0$ s, for identifying the reference frame origin); position in the middle of PP phase; position at the end of TP and position at a frame in RP. These are repeated in each poling cycle performed.

occurs during the early stage of the push phase. To assess this, using kinematic and anthropometric data, normalized inertial forces of the upper body have been estimated.

Subject and methods

The cross sectional study had been carried out during 2010 Paralympic Games in Vancouver during 1 km-sprint competition.

Participants

Athletes belonging to the most impaired class (LW10) were video recorded during each round of the 1-km sprint race. Analysed video sequences were referred to a group of 7 participants: 3 men (age, 42.3 ± 4.0 y) and 4 women (age, 38.7 ± 7.0 y). All sit-skiers were eligible to participate in the study.

Data acquisition

A camera (BASLER scA640-120fc, zoom lens GMZ8048010MCN) working at 90 fps was located on a rectilinear segment with a slope of 2% at the middle–last third of the competition course. The camera was placed perpendicular to the tracks. Participants were filmed from one side, on the sagittal plane, during different matches in the same section of track. No markers were placed on the athletes' suits nor on the equipment, due to the competition context. Some techniques for motion analysis based on features detection and point tracking are described in [13–15]. Video-recordings and image analysis were possible by means of a markerless analysis system based on digital cameras, working at a frequency of 90 fps. This frame rate was greater both with respect to that one of the gesture (normally around 2 *Hz* for standing athletes) and with respect to what is reported in the literature [16] in order to adequately capture XC sit skiers cycle biomechanics. Due to the peculiarity of the competition, as well to the stadium scenario in which it occurred, only one camera could be used, allowing only a 2D kinematical analysis.

Nevertheless, important information about the cycle can be gathered from a sagittal plane analysis, according to the considerations regarding standing athletes made by Stoggl and Holmberg [17].

Biomechanical model

In order to acquire human motion data and to associate these to a proper model related to the case study, a biomechanical model within its relative points of interest was used as reference (Fig. 3A). For the body 7 anatomical points are taken into account: head (He), shoulder (Sh), elbow (El), wrist (Wr), hip (Hi) joints, and, when appropriate, knee (Kn) and ankle (An) ones. Moreover, 4 technical points are added to identify the pole and the sledge: upper grip point (GPu), down grip point (GPd) and tip point (PT) on the pole and one point for the sledge (Sl).

All the points were projected on the sagittal plane to compute the 2D analysis. A global reference frame was introduced to define position, velocity and acceleration vectors for all the points. According to this system, both anatomical and technical points were tracked and their absolute coordinates were computed and smoothed with a moving averaged filter with a radius of 2 frames.

Besides, relative angles between body segments were identified: the elbow angle (θ_e), between upper arm and forearm, and the shoulder angle (θ_s) between upper arm and trunk. For what concerning the trunk and the pole tilt angles (θ_t and θ_p), measurements were carried out with respect to the ground vertical axis, with a proper direction of rotation (Fig. 3B).

Kinematic variables, as positions, velocities and accelerations were defined for both the anatomical points and the technical ones. In addition, absolute angular velocities ($\mathbf{w}_\mathrm{f}$ and $\mathbf{w}_\mathrm{u}$), as well angular accelerations ($\dot{\mathbf{w}}_\mathrm{f}$ and $\dot{\mathbf{w}}_\mathrm{u}$) were considered for the forearm and the upper arm respectively.

Symmetry of the movement respect to the sagittal plane was expected, since the trial was recorded on a straight track. Nevertheless symmetry was visually checked for all athletes on the videos; hence data were processed only for one side, assuming an overall condition of symmetry for the whole body.

Estimation of the inertial effect contribution

Regarding the purposes of this study to assess of an inertial propulsive force provided from the upper body region, acceleration of body segments had to be analysed. Both arms and trunk contributions were considered, although the trunk one was negligible in case of LW10 athletes, with respect to the force provided from arm-segments.

Upper arm and forearm body segments were modelled as two links connected in the El joint (Fig. 3C and D). The upper arm link can be identified with the joints Sh and the El, allowing its articulation to the trunk and to the forearm respectively. Similarly, the forearm link is identified with the joints El and Wr, allowing it to be articulated to the upper arm and the hand respectively. Upper arm and forearm length were physically measured on the athletes. Based on this direct measurements, the location $\mathrm{L_{CMu}}$ and $\mathrm{L_{CMf}}$ of the relative centres of mass $\mathrm{CM_u}$ and $\mathrm{CM_f}$ have been estimated using the geometrical ratios f and u for the forearm and upper arm respectively [18]. These ratios were both calculated from the distal joint of each link, in order to properly locate the centres of mass, as follows:

$$L_{\mathrm{CM_f}} = f \cdot \mathrm{forearm_{length}}$$

$$L_{\mathrm{CM_u}} = u \cdot \mathrm{upperarm_{length}}$$

Positions ($\vec{\mathbf{p}}$), velocities ($\vec{\mathbf{v}}$) and accelerations ($\vec{\mathbf{a}}$) vectors of both $\mathrm{CM_f}$ and $\mathrm{CM_u}$ can be defined according to the following equations (Eqs. (1)–(6)), by means of known variables that are used and detailed in Table 1:

$$\vec{\mathbf{p}}_{\mathrm{CMf}} = \vec{\mathbf{p}}_{\mathrm{E}} + f \cdot (\vec{\mathbf{p}}_{\mathrm{W}} - \vec{\mathbf{p}}_{\mathrm{E}}) \tag{1}$$

$$\vec{\mathbf{v}}_{\mathrm{CMf}} = \vec{\mathbf{v}}_{\mathrm{E}} + f \cdot [\vec{\mathbf{w}}_{\mathrm{f}} \times (\vec{\mathbf{p}}_{\mathrm{W}} - \vec{\mathbf{p}}_{\mathrm{E}})] \tag{2}$$

$$\begin{aligned}\vec{\mathbf{a}}_{\mathrm{CMf}} = \vec{\mathbf{a}}_{\mathrm{E}} &+ f \cdot [\vec{\dot{\mathbf{w}}}_{\mathrm{f}} \times (\vec{\mathbf{p}}_{\mathrm{W}} - \vec{\mathbf{p}}_{\mathrm{E}})] \\ &+ f \cdot [\vec{\mathbf{w}}_{\mathrm{f}} \times [\vec{\mathbf{w}}_{\mathrm{f}} \times (\vec{\mathbf{p}}_{\mathrm{W}} - \vec{\mathbf{p}}_{\mathrm{E}})]]\end{aligned} \tag{3}$$

$$\vec{\mathbf{p}}_{\mathrm{CMu}} = \vec{\mathbf{p}}_{\mathrm{S}} + u \cdot (\vec{\mathbf{p}}_{\mathrm{E}} - \vec{\mathbf{p}}_{\mathrm{S}}) \tag{4}$$

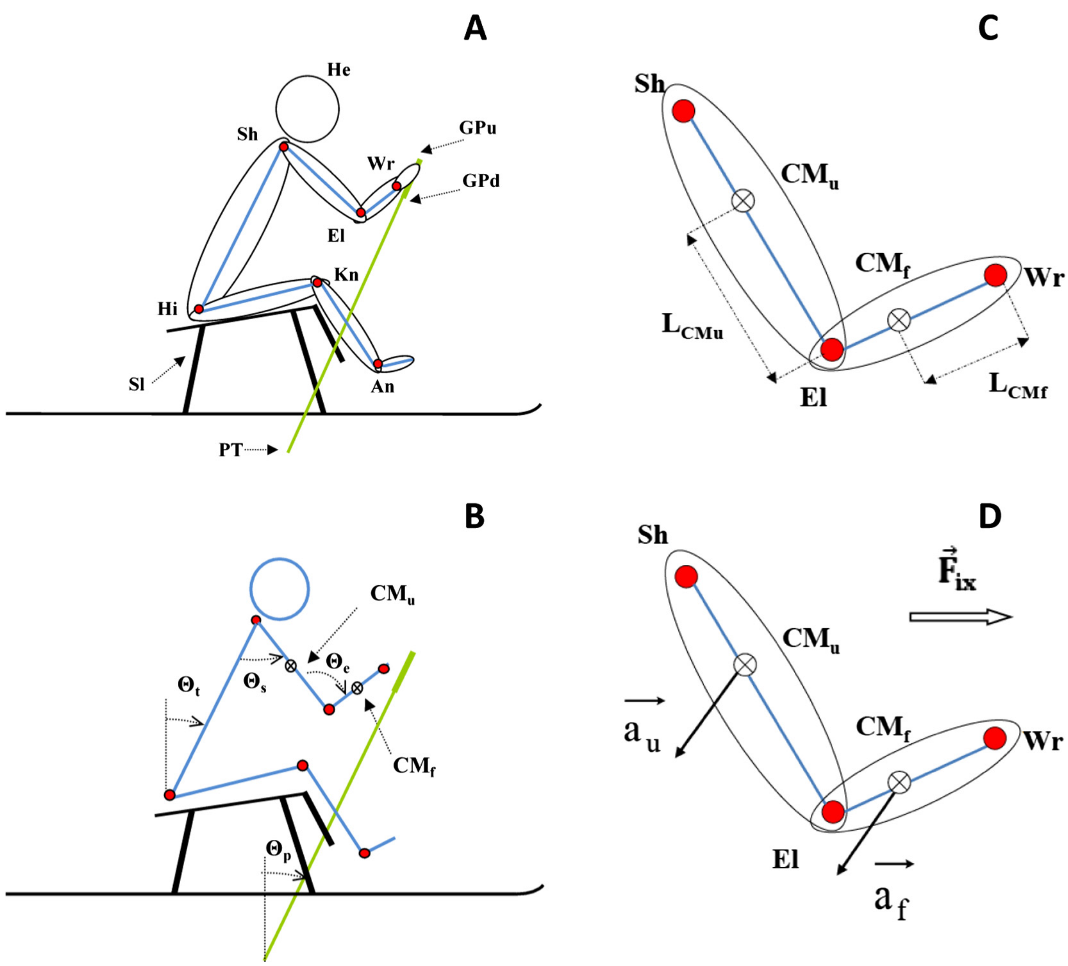

Fig. 3 Biomechanical models. (A) Body stick diagram projected on the sagittal plane with anatomical points (head temple (He), shoulder (Sh), elbow (El), wrist (Wr), hip (Hi), knee (Kn), ankle (An)) and technical points (3 for the pole GPu, GPd, PT and 1 for the sledge (Sl)). (B) Body stick diagram projected on the sagittal plane with the additional computed points and angles: CM_u and CM_f like the centres of mass of upper arm and forearm respectively, elbow angle (θ_e), shoulder angle (θ_s), trunk and pole tilt angles θ_t and θ_p measured with respect to the ground vertical axis. Angles chosen according to the proper direction of rotation. (C) Model of the forearm and upper arm body segments connected each other in the El joint. Sh and Wr joints, along with both centres of masses CM_f and CM_u with their relative location L_{CMf} and L_{CMu} from the distal joint of each body segment. (D) Model of the forearm and upper arm body segments with relative total acceleration vectors $\vec{a_f}$ and $\vec{a_u}$ respectively, along with the inertial force $\overrightarrow{F_{ix}}$ providing propulsion.

$$\vec{\mathbf{v}}_{CMu} = \vec{\mathbf{v}}_S + u \cdot [\vec{\mathbf{w}}_u \times (\vec{\mathbf{p}}_E - \vec{\mathbf{p}}_s)] \tag{5}$$

$$\vec{\mathbf{a}}_{CMu} = \vec{\mathbf{a}}_s + u \cdot [\vec{\dot{\mathbf{w}}}_u \times (\vec{\mathbf{p}}_E - \vec{\mathbf{p}}_S)] + \mathrm{u} \cdot [\vec{\mathbf{w}}_u \times [\vec{\mathbf{w}}_u \times (\vec{\mathbf{p}}_E - \vec{\mathbf{p}}_S)]] \tag{6}$$

Starting from the total body mass m_t of the athletes recorded during the Paralympic Games, masses of upper arm m_u and forearm m_f were estimated according to the regression equations presented in the literature [19–21], taking into account the different parameters for male and female. Once the kinematics has been analysed, an inertial force $\vec{\mathbf{F}}_{ix}$ normalized with respect to the total mass of the considered arm m_a, acting along the propulsive-pushing direction, has been computed, as follows:

$$\vec{\mathbf{F}}_{ix} = -[(m_u \cdot \vec{\mathbf{a}}_{CMu} + m_f \cdot \vec{\mathbf{a}}_{CMf})/m_a] \cdot \vec{\mathbf{i}} \tag{7}$$

Results

The assessment of the acceleration due to the net contribution of both the upper and forearm, properly weighted according to the ratio of mass of each arm-body segment, compared to that one of the sledge can be observed (Fig. 4A). In the time interval from $t = 0$ s to $t = 0.13$ s the greatest increase of sledge acceleration can be seen. This is justified by the inertial effect due to the arms motion which allows the sledge progression in that interval. The inertial force providing sledge propulsion is reported in Fig. 4B. Due to the symmetry condition, the inertial force normalized with respect to the athlete's arm weight and computed according to Eq. (7), can be considered twice in order to evaluate both arms inertial contribution. In the specific case reported in Fig. 4B, the force reaches a peak value around 24 N/kg.

Table 1 Variables used in Eqs. (1)–(6) for the final computation of the inertial force contribution.

Terms	Description
$\vec{p}_S$	Position vector of **Sh** joint
$\vec{p}_E$	Position vector of **El** joint
$\vec{p}_W$	Position vector of **Wr** joint
$\vec{p}_{CMu}$	Position vector of $\mathbf{CM_u}$ joint
$\vec{p}_{CMf}$	Position vector of $\mathbf{CM_f}$ joint
$\vec{v}_S$	Velocity vector of **Sh** joint
$\vec{v}_E$	Velocity vector of **El** joint
$\vec{v}_{CMu}$	Velocity vector of $\mathbf{CM_u}$ point
$\vec{v}_{CMf}$	Velocity vector of $\mathbf{CM_f}$ point
$\vec{a}_S$	Acceleration vector of **Sh** joint
$\vec{a}_E$	Acceleration vector of **El** joint
$\vec{a}_{CMu}$	Acceleration vector of $\mathbf{CM_u}$ point
$\vec{a}_{CMf}$	Acceleration vector of $\mathbf{CM_f}$ point
$\vec{w}_f$	Angular velocity of **forearm** segment
$\vec{w}_u$	Angular velocity of **upper-arm** segment
$\dot{\vec{w}}_f$	Angular acceleration of **forearm** segment
$\dot{\vec{w}}_u$	Angular acceleration of **upper-arm** segment

Table 2 Mean value and standard deviation of the peak force and of the time at which the peak occurs expressed as a function of the cycle percentage.

Terms	Peak force [N]		Peak time [%cycle]	
	Mean	SD	Mean	SD
Men	34.1	3.4	22.3	1.5
Women	23.2	3.1	23.8	2.6
All	27.9	5.6	23.2	2.2

In Table 2, for all the athletes and also separately for gender, the mean value and standard deviation of the peak force and of the time at which the peak occurs expressed as a function of the cycle percentage are reported.

Discussion

The contribution of the arm had been assessed in several studies with able-bodied athletes, both in DP and skating techniques [22–24]. In particular arm swings contribute considerably to the overall force generation and propulsion. The main findings of this study regard the evaluation of the inertial effect contribution of arms that are responsible for a significant increase of sledge velocity, hence of a propulsive action during the initial poling phase accomplished by LW10 Paralympic XC sit-skiers. The abrupt arm lowering, similarly to what happened in able-bodied subjects, is expected to be beneficial also for the pole plant force, however this cannot be assessed just using kinematic data and specific tests have to be performed.

The contribution of the trunk was tested, but it is not reported because it represented a negligible contribution to the propulsion. As a matter of fact even if the trunk mass is high, the acceleration of the trunk is insignificant; then the resulting inertia force was lower that 2% with respect to the arms one.

Significant statistics cannot be provided, mainly due to the small sample size data, also considering that there are few ath-

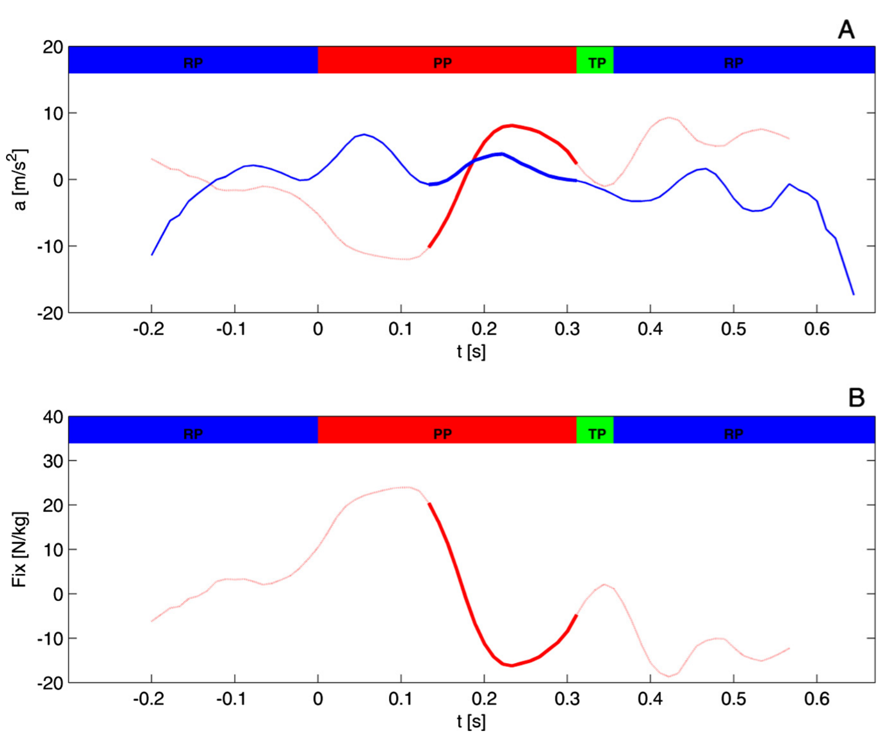

Fig. 4 Assessment of the inertial effect providing sledge propulsion in the initial PP (from t = 0 s to t = 0.13 s). (A) Comparison between sledge acceleration (blue solid line) and global effect of arm acceleration (red dashed dotted line). (B) Normalized inertial force F_{ix}, due to both arms segments motion providing sledge propulsion.

letes belonging to LW10 class worldwide. Nevertheless some consideration can be withdrawn from the present study.

The DP technique of sit skiers is mainly a 2D gesture providing sledge progression during this practice. As an overall trend, considering athletes of all the classes, the pushing cycle can be assumed as an upper-body action, particularly involving trunk and the arms in performing it. Indeed during this activity, a complex variability in terms of slope, sitting posture and the sledge or other equipment design has to be considered. For what concerning particularly the sitting posture, the presence or not of the abdominal muscles is effective in force generation. Indeed it represents the main difference between athletes of LW10 class, with a complete impairment of the lower trunk control, respect to athletes of higher class for which the previous function is only partially impaired or completely unaffected. For those whose abdominal function is completely absent, trunk flexion is obtained thanks to the gravity force, while extension is obtained by compensation mechanisms that exploit head, arms and upper trunk inertia. Besides, the absence of abdominal and extensor muscles influences also the sledge shape and the seat posture: straps and knee-high position limit the trunk flexion [4].

The assessment of the total propulsive inertial effect due to the arms actions during the observed interval is here outlined. Despite the short duration of this temporal window, a steepest rise of sledge velocity can be observed prior to the effective pushing poles contacts on the terrain (Fig. 2B). The sledge propulsion is provided by the inertial effect, mainly due to the upper body region (arms and forearms) movement. According to the formulas and the reasoning explained before, there is a normalized propulsive inertial force with a peak value. This acts as a propulsive force and the result is a significant sledge fastening, corresponding to the onset of PP and prior to the pole planting.

Thus, it is clear how this amount could be greater for those athletes whose abdominal muscles, hence trunk control, are allowed, due to the addition of the trunk body segment inertial contribution. Athletes with different impairments, and hence belonging to different classes, may benefit differently from this propulsive effect.

The findings of the present study have a direct practical implication for a better understanding of the technique in competitive cross-country sit-skiing and for training. Future tests should further investigate the biomechanical aspects of different strategies of the arm motion in the early phase of PP, the relationship with physiological variables, and elaborate specific strength and technical strategies to measure and increase performance. Each athlete can train and optimize this gesture in order to maximally exploit the propulsion and the present methodology may be applied to quantify the achieved contribution.

Limitations of the study are related to the estimation of arm segment masses, since it is based on tables for able-bodied individuals and not on subject-specific models [25,26]. Usually many wheelchair users have hypertrophied arms. Since it was not possible to directly measure inertial limb properties, due to the operative contest, the use of able-bodied data assumption is precautionary. Furthermore, in a non-racing contest or in laboratory tests more accurate kinematic measurements can be obtained using technologies that are already well-assessed in clinical environment e.g. electrogoniometers [27,28], inertial sensors [29] or marker stereophotogrammetric analysis [30].

Another study limitation is the small number of athletes, which is a common problem when dealing with Paralympic athletes.

Conclusions

In the pushing techniques adopted by sit-skiers an important contribution is given by abrupt arms and trunk movements at the beginning of the poling phase, prior to the poles impact. The associated inertial contribution is useful to achieve sledge propulsion with a steepest increase of velocity. In this study this inertial effect, as responsible for a propulsive action of the sledge, has been assessed in LW10 Paralympic XC sit-skiers.

Conflict of Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from all patients for being included in the study.

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