DEVELOPMENT AND VALIDATION OF A SYSTEM FOR POLING FORCE MEASUREMENT IN CROSS-COUNTRY SKIING AND NORDIC WALKING

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The purpose of this study was to describe and validate a force transducer system specifically designed to measure the force exerted through the poles in cross-country skiing and Nordic walking. It is constituted by a custom built load cell and by a mounting system that allow to minimise cross talk effects. The system is applicable to standard carbon racing shafts to ensure the standard stiffness of the pole. The reliability of the system has been tested performing different static and dynamic tests. The comparison with the reference load cell has shown a good measurement linearity in the range of typical values for poling propulsion and a sensitivity only to the force axially applied to the shaft. The test performed on a 2D platform and with a motion capture system for the measurement of pole inclination, demonstrated the possibility to obtain a reliable measure of the vertical, longitudinal and lateral components of the force exerted by the subject. The accuracy, the portability of the system and their applicability to different shafts allow evaluation of poling action in both laboratory and field conditions, providing important information in cross-country skiing and Nordic walking biomechanical research.

KEY WORDS: Nordic walking, cross-country skiing, force, poles, validity.

INTRODUCTION: The increasing number of studies published in recent years highlights the growing interest in understanding the contribution of upper limbs in different forms of locomotion such as cross-country skiing and Nordic walking. Early studies investigated the forces applied on the poles during cross country skiing (Pierce, 1987). In the last few years, the interest in Nordic walking as health-enhancing physical activity has also increased the interest in the analysis of the propulsive role of the upper limbs in non purely sporting contexts. The quantification of the forces applied through the poles can be obtained using traditional and special force platforms, or force transducers mounted on the poles, (Komi, 1987, Holmberg et al., 2005). A limitation of force platform is that the measurements are obtained on just on one or few consecutive poling cycles. Furthermore, this measure can be collected during a limited range of conditions (Komi, 1987) To overcome these shortcomings, the use of force transducers mounted below the poles handgrip has been developed and proposed (Holmberg et al., 2005). This method is more advantageous in terms of portability and increases the range of conditions that can be investigated. Recently, commercial handgrips for both cross-country skiing and Nordic walking poles have been modified by replacing the old wrist strap with a wrapper cuff. This new solution reduces the hand control on the grip and moves away the force point application from the axis of the pole. To minimize the cross talk due to bending moment a new system has been developed. The aims of this study were to describe the system and to examine its accuracy and reliability in acquiring the force exerted through the poles during skiing and Nordic walking.

METHODS: Force measurement system: A mono axial custom made load cell (Deltatech, Italy) was mounted between the upper end of the shaft and the handgrip. The transducer was calibrated using a specific calibration apparatus with 6 standard weights (5-30 kg). The hand-grip has been modified by inserting an aluminium pipe that permits a free longitudinal movement of the handle respect to the shaft (Figure 1). In this way only the axial force is transmitted by the load cell from the handgrip to the section of the pole, while the transverse forces are unburden by the coaxial aluminium pipe. The movement of aluminium pipe and hand grip is limited by a rubber band that maintains the cell preloaded. The load cell is retained in the correct position by a light pipe cemented with the cell and that contains the amplifier. The load cell and amplifier power dissipation is about 200 mW . To allow the individual selection of the poles length and to ensure the standard stiffness of the pole, the traditional carbon racing shafts (CT1; Swix Sport, Norway; Diamond 10 Max; One Way, Finland) with different lengths (115 cm-170 cm, 2.5 cm steps) were used. The weight of the load cell is 30 g and the entire measurement system adds 50 g to the original pole mass. A further increment in the pole mass is due to the special carbide tip (49 g) that is used when the tests are performed in the lab to allow a suitable friction with the rubber surface of the treadmill. The position of the centre of mass does not change after applying the force measurement system and the special tip (64.5 vs. 64.7% of pole length), while rises until the 70.8% of pole length with standard tip.

Experimental testing and data analysis: Different statical and dynamical tests were performed in order to assess the reliability of the force measurement system. All signals were acquired by means of a data acquisition board (NI DAQ-PAD-6016, 16 bit; National Instruments, USA), while the inclination and the motion of the pole in the different setups were collected at 200 Hz by means of an optoelectronic motion capture system (6 cameras MCU240, ProReflex; Qualisys, Sweden). Five reflective markers were axially adhered along the pole at a distance of 20 cm between each other. Data collection was triggered by a digital signal in order to ensure the synchronization between force and kinematic signals.

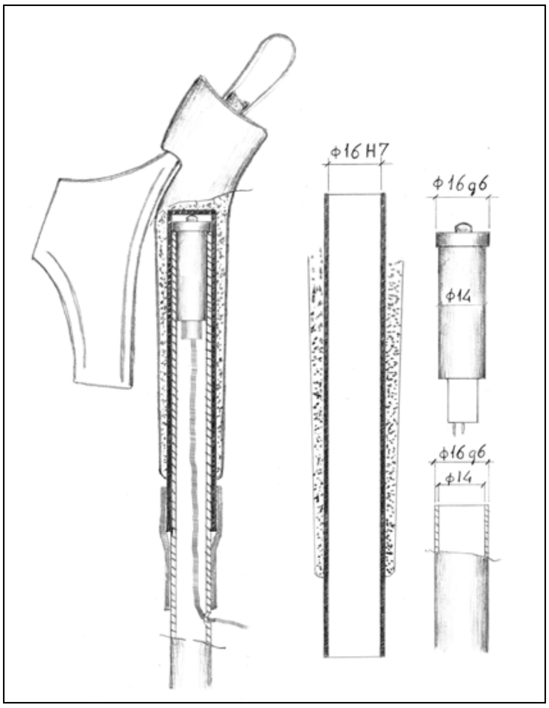

Figure 1: Drawing of the load cell and its position under the handgrip

1. A static test was conducted to analyse the measures obtained when a non-axial force is applied. The test was performed suspending a mass of 4 kg to the strap and inclining the pole at different tilt angles. The measured values were compared with the theoretical values calculated as the product of the weight force by the sine of the tilt angle.
2. A validation of the measurement system linearity was performed by axially pushing the instrumented pole against a reference load cell (546QD; DSEurope, Italy) simulating 15 poling cycles. Both signals were sampled at 200 Hz.
3. Five poling imitation at every five different pole inclinations were performed on a two axial force platform (P114-BIAX-S-A/5000N; Deltatech, Italy) maintaining the pole on the XZ plane. The pole force has been factorized in longitudinal (X) and vertical (Z) force as product of pole force by the cosine and the sine respectively of the angle between the line through the 1st and the 5th marker and horizontal line. The calculated longitudinal and vertical forces have been then compared with the respective force components acquired by the force platform.
4. The accuracy of the device in dynamic conditions was examined measuring the resonant frequency of the dynamometric system. The load cell mounted on the specific calibration apparatus and the whole system were impacted with a hard plastic hammer on the upper side of the hand grip. Force signal was acquired at 10 kHz.
5. To test the response of the pole during force action, a double-poling exercise was performed on a treadmill using roller skis. The flexion of the pole was determined by measuring the camber of the shaft under loading condition. An athlete skied at 13 km·h^{-1} at 3° of slope. A 30 seconds recording period was acquired at 200 Hz by the kinematic system. The camber was evaluated analysing the maximal displacement between the line through the 1st and the 5th marker and 3rd degrees polynomial curve that fits all pole markers.

RESULTS:

1. The difference between the measured and the reference values is reported as absolute and percentage difference respect to the full scale at different pole inclinations.

Table 1: Results of static measurement at different pole inclination

Inclination [°]	78.1	63.1	53.7	49.2	36.3
Measured [N]	38.18 ±0.17	35.25 ±0.15	31.26 ±0.14	28.74 ±0.12	23.98 ±0.10
Theoretical [N]	38.40	34.99	31.62	29.70	23.23
Abs error [N]	-0.22	0.25	-0.37	-0.96	0.75
Error/FSD [%]	-0.04	0.05	-0.07	-0.19	0.15

2. Coefficient for the linear regression between reference load cell value and pole force measurement is 0.999 ($p<0.001$) while the constant coefficient of the equation for the linear regression is -4.025 (Figure 2).

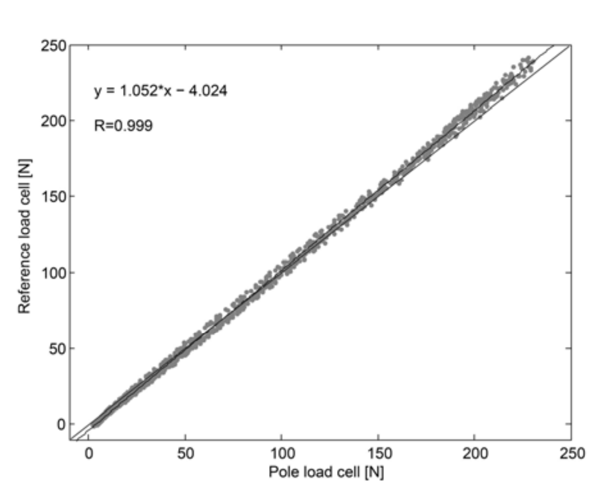

Figure 2: Regression between pole load cell and reference load cell.

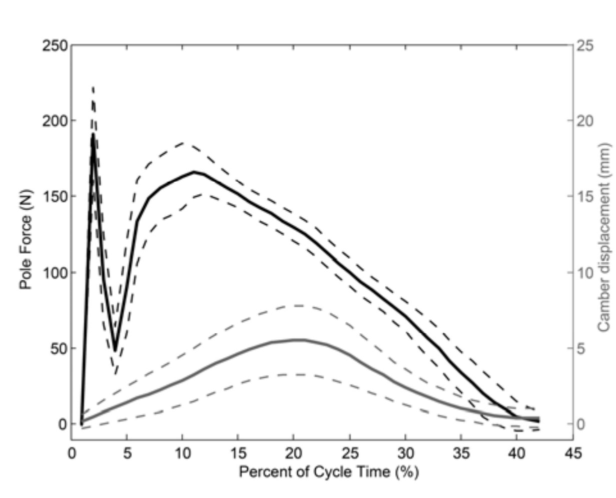

Figure 3: Typical curve for poling force for double poling (black line) and measure of the camber of the shaft (grey line).

3. The difference between the force measured by the pole force transducer and force platform was calculated as percentage with respect to full scale for both vertical (Z axis) and longitudinal (X axis) components. A relation between the magnitude of the error and the absolute values was found for the vertical component. Specifically, the lowest the pole angle the highest the difference between the two measures.

Table 2: Results of poling imitation test at different pole inclination

Inclination [°]	88.2 ±0.65	64 ±0.71	47.5 ±1.66	41.5 ±0.78	34.9 ±0.90
Error/FSD Z [%]	1.01 ±0.75	1.13 ±1.19	1.23 ±1.44	1.83 ±2.35	3.03 ±2.74
Error/FSD X [%]	-0.03 ±0.46	-0.45 ±0.62	-0.74 ±1.00	-0.31 ±1.77	0.61 ±2.55

4. No resonant frequency has found for the load cell transducer while a 39.6Hz resonant frequency was found for the complete system (measurement equipment and pole).

5. A small but significant flexion of the pole during the poling action was found (Figure 3). The maximal camber is 5.5 ±2.2 mm occurring at about 20% of the poling cycle time.

DISCUSSION: The results of this study support the validity of a new force transducer system for measuring the force exerted through the poles. The insertion of the force measurement system to the traditional racing pole increased the original weight but did not change its centre of mass. This is particularly appreciated by the elite athletes that referred their technical action was not modified by the modified poles. The static test showed that the transducer inserted on the pole is sensitive only to the force axially applied to the shaft, indicating that the measurement is minimally corrupted by cross-talk effect. This result was confirmed in the dynamical situation. Indeed, the test performed on the 2D platform showed that almost all the force applied along the pole was accounted by the longitudinal and vertical force components. This also demonstrated that with a system that can measure the inclination of the pole, it is possible to obtain a reliable measure of the vertical, longitudinal and lateral components, and not only the total component of the force exerted by the subject. This decomposition is particularly important because it allows to identify the components that effectively contribute to the forward propulsion. The comparison with the reference load cell has shown a good measurement linearity in the range of typical values for poling propulsion (Holmberg et al., 2005). However, the offset resulting from the regression equation suggested that the assembling of the transducer and the handgrip using the rubber caused a preload of the load cell. To take in account this preload that could be different for each system, we suggest to perform a calibration before every test. No resonance frequency is associated to the transducer while an oscillation has been seen for the complete system probably due to the shaft vibration. However the results of double poling test on the treadmill showed no effects of vibration during typical poling force exertion. A slight flexion during double poling actions of the shaft was detected during the test performed in specific condition. Further studies are needed to examine if camber and vibration are related to pole length, pole stiffness and/or ground hardness. The low energy consumption and the range of the output signal of this load cell are well suited for a portable pole measurement system since it is only necessary to add small batteries and a portable datalogger.

CONCLUSION: This study demonstrated the accuracy and reliability of this new force transducer system specifically designed to measure poling force. The main advantage of this system is to minimize the cross talk effect due to the bending moment allowing the measure of the force exerted through the pole. Furthermore, combining kinematic data, it allows to determine longitudinal force to better understand the contribution of the poling action in cross-country skiing and Nordic walking biomechanical research. The portability of the system and their simple applicability to the different type of shafts allow to evaluate poling contribution in both controlled (laboratory) and ecological (field) conditions.

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