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VALIDATION OF A 5-DOF INSTRUMENTED SPEED SKATE; TOWARDS A POWER METER FOR SPEED SKATING

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Speed skates are the most important part of equipment of a speed skater, where weight, rocker and bend are just a few characteristics that are to a high degree individualized. This poses a challenge for any type of research in speed skating where forces have to be measured in a reliable manner. For this purpose, a 5 degrees of freedom (DoF) instrumented speed skate (VU-Skate) has been designed and validated, weighing only 130 gram extra. Skaters use their own blades and shoes, something skaters are very keen on. A calibration tool has been developed to calibrate the 5 DoF. The quality of the data has been validated in 2 ways: 1. With the use of force plates and 2. By comparing the signals to another (also newly developed) Ultra-light Forces sensor. The results are remarkably good. This is the first step in being able to measure power continuously during each stroke.

KEYWORDS: speed skating, instrumented speed skate, dynamic forces and moments

INTRODUCTION: In several sports it is now quite common to measure the forces applied by the athlete to the external environment and for any self-respecting cyclist it is unimaginable not to use a power meter. A power meter for speed skating is probably number one on the wish list of a coach. Unfortunately, such a device poses a number of engineering challenges. For one, implementation in a speed skate, where weight, dimensions and 'feel', like stiffness are critical, and second, a skate moves with respect to the ice even during the push-off phase. The later hampers the estimation of speed and its direction of both skate and Center of Mass (CoM) of the speed skater and since the direction of the push-off (force) is almost perpendicular to the forward movement of the center of mass of the speed skater(Koning, Boer, Groot, & Schenau, 1987), errors in angle estimation between force- and velocity-direction can be come large. As power is defined as the force applied times velocity, the challenge is evident. The Instrumented speed skate is one part of the puzzle towards accurate power estimation per stroke.

In the past, several instrumented skates have been designed (Houdijk et al., 2000; Koning, Groot, & Schenau, 1992; Kruk, Braver, Schwab, Helm, & Veeger, 2016; Yuda, Yuki, Aoyanagi, & Fujii, 2004) None, however, were able to measure 5 degrees of freedom (5-DoF) in a klap skate with a low additional weight and provide real-time feedback.

The forces and moments applied by the skater will already provide new insights in differences in performance between skaters and the interaction between skater and blade: at what time in the stroke does the force reach its maximum? What is the magnitude of the horizontal force during the push-off? The VU-Skate measures three moments around the principal axis of the skate (Figure 1). The moment around the transverse axis (M_x) shows the center of pressure (CoP) and defines when the klap skate opens. The moment along the sagittal/anteroposterior axis (M_y) gives an estimate of the displacement of the vertical force perpendicular to the blade. A skater 'creates' moments to either influence the steering of the skate or (e.g.) to counteract an upper body rotation. Forced steering of a skate could lead to an increase in ice friction. The VU-Skate is integrated in the already existing platform of sensors to investigate the kinematics of individual skaters while training (Eb et al., 2018; Eb et al., 2017)

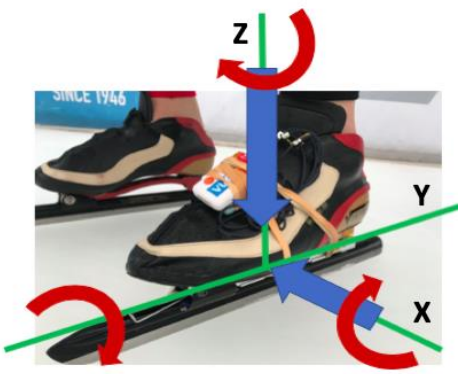

Figure 1. Vu-Skate with all the forces (F_x, F_z) and moments (M_x, M_y, M_z)

In this paper the validation of the VU-Skate and some preliminary results showing the wealth of information will be discussed.

METHODS: The VU-Skate is calibrated using a custom-made calibration setup were both vertical and horizontal forces can be applied at different positions along the blade. For the purpose of calibration six points on the blade were loaded with 3 vertical forces, ranging between 0-1000 N and for every vertical force 5 horizontal loads between 0-200 N. 10 Seconds (128 Hz) for each calibration measurement were recorded and averaged. From the applied forces and positions on the blade together with the measured values from the VU-Skate a sensitivity matrix is calculated, comparable to a force plate calibration. Taking raw data from the VU-Skate and multiplying these with the sensitivity matrix results in two forces, F_x and F_z, and 3 moments around the axis of the skate. The results of first test runs are promising and more data will be collected this winter at high speeds.
Although the calibrated data from the VU-Skate show the features one would expect, it is still important to validate the calibrated results in a dynamic situation. Using two different techniques the validity of the output is compared: 1) with data from a calibrated force plate and 2) with data from Ultra-light Forces sensors (UFs, developed in the same project that will be presented elsewhere).

A calibrated 6-DoF Kistler Force plate is used to verify the output of the VU-Skate. For this purpose, the skates are worn and placed individually on a separate force plate (bare blades on a thin rubbed mat to protect the blade). During one minute typical skating moves were performed. Data of both systems are compared, and shown in Figure 2 left. To validate the measured horizontal forces of the VU-Skate a moment was applied while standing on one skate on the force plate. To apply a moment on the skate with the foot a hand pressed against a vertical support. Care has been taken to avoid introducing new forces other than torques around the vertical axis, as well as possible, see Figure 2 right side.

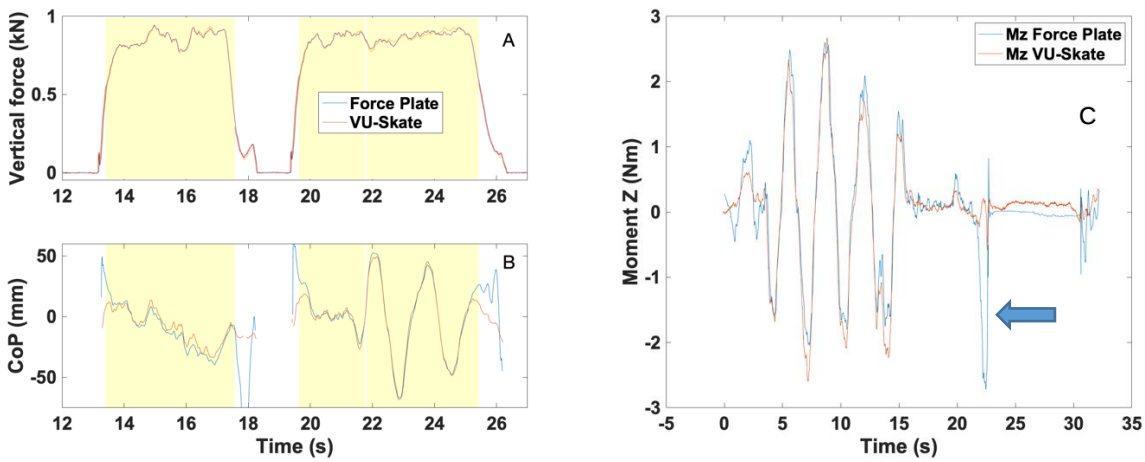

Figure 2. A. vertical forces (RMSE = 38 N) and A. center of pressure of the VU-Skate and Force plate are compared. C. (Right) The Z-moment measured by the Force plate and VU-Skate. Arrow indicates depicts the large deviation were the klap skate opens (RMSE = 0.3 Nm)

For the second validation test, the UFs are mounted on the VU-Skate, recording simultaneously. While skating on ice, the two measurement systems collected data

independently. The UFs measure forces only in the vertical direction and thus only provide the total vertical force and the center of pressure (CoP) in the anteroposterior direction of the skate; a much simpler system weighing less then 40 grams including electronics. An example of the vertical force and CoP are shown in Figure 3.

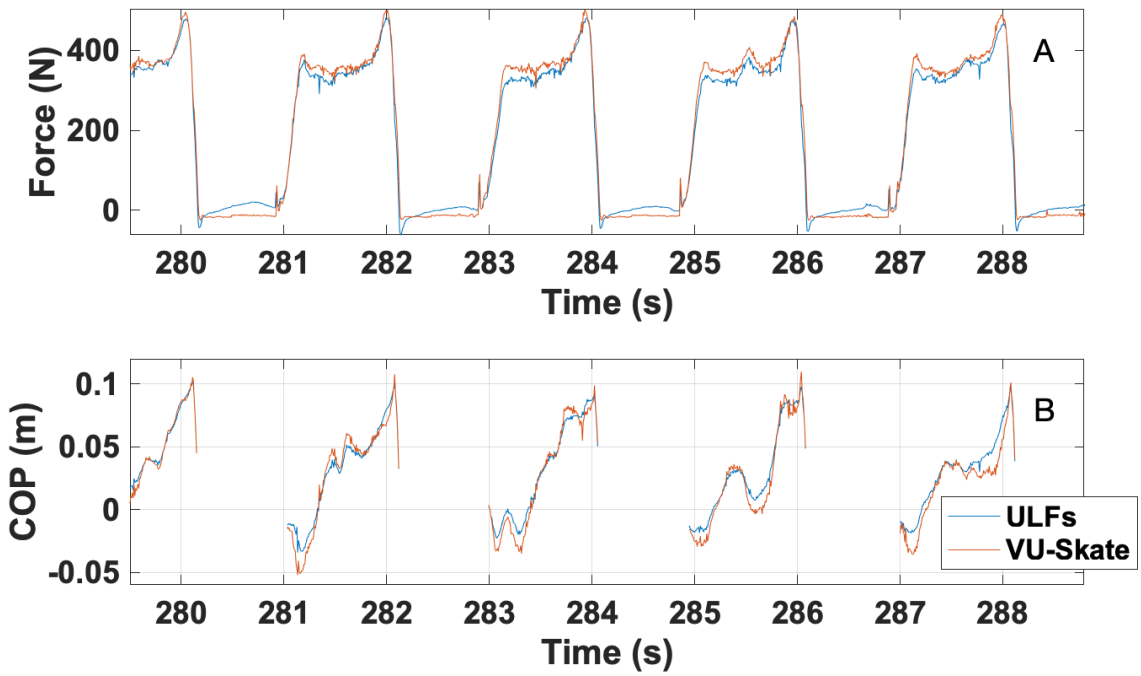

Figure 3. Example of 4 strokes, A. showing the Vertical force measured with the VU-Skate (red) and the UFs sensors (blue). B. CoP of the force along the blade.

RESULTS: Both validation experiments show overall good observational qualitative agreement between the calibrated VU-skate for the vertical, Center of Pressure (CoP) in posteroanterior direction and the moment around the vertical (z) axis. The Root Mean Square Errors (RMSE) are provided for figure 2. Moment, M_z, deduced from the 2 horizontal force transducers, shows good agreement with the force plate data. For lower vertical forces the CoP of the force plate starts deviating from that of the VU-Skate (Figure 2B). This is seen before the onset and after the drop at the end of each loading phase. Not only the force decreases sharply here, but also the skate starts tilting as the Center of Mass (CoM) of the skater moves away from the vertical (falling).

DISCUSSION: The observation that two completely different measurement systems, the force plate and the 'embedded' UFs sensors, show such good agreement with the calibrated data, is a strong indication for quality of the instrumented skate. Especially in the high dynamical environment involving high speeds, loads and accelerations of skate and skater it will provide new insights into the mechanics of the push-off. Having said that, there are unresolved issues as well: how does the skate behave at high speeds above 40 km/h, which is typical of elite level speed skating? How much will the added weight, although considered minor for ambulant force sensors, and stiffness influence the skater at high speeds? For this reason, much lighter 2 DoF sensors, UFs, are developed simultaneously. They are expected to provide at least part of the information at maximum speeds (up to 60 km/h).
The remaining errors in mainly the CoP can partly be attributed to the way the Calibration device is designed. Vertical and horizontal forces are applied simultaneously but independently on the same point on the blade. Since blade and bridge will bend under the loading, misalignment will occur and thus the exact loading will deviate somewhat from the applied forces. The next technical step will be to redesign the calibration device. At the end of the push-

off the klap skate opens, and the force will propagate through the skate in a different manner. The calibration routine will have to incorporate this in the future.

CONCLUSION: The VU-Skate provides a unique window into the complicated and dynamical behavior of the speed skate during push-off. The moments applied by the skater on the skate are expected to shed light on the ways individual skaters steer their skate over the ice. The force profile during a stroke will be used to optimize the effectiveness of the push-off.
The forces measured during the push-off are an essential ingredient for measuring power per stroke. Measurement of effective power output is hampered due to the fact that skates move almost frictionless over the ice during push-off, nevertheless an estimate of power per stroke, whether it contributes to the forward velocity or not, will be possible with the VU-skate in the near future. This is one of the two essential ingredients for power estimation. The next technical development will be to integrate the measurement of the velocity of the center of mass of the skater relative to the skate.
The VU-Skate will now be used to provide individualized feedback on skating technique and may in the future help to customize the blade for an individual skater.

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