ACTA UNIVERSITATIS CAROLINAE,
KINANTHROPOLOGICA Vol. 46, 2 – 2010 Pag. 53–65

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THE DETECTION OF LOADING FORCES EXERTED ON THE SKATE AND SOLE OF THE FOOT DURING SKATING

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SUMMARY

Measurement of loading forces acting on the foot is measured with respect to long-term normal movements such as walking, running, jumping and more. These measurements are carried out barefoot and using shoes (Klenerman, Wood 2006, Meldrum Hilton, 2004). Significantly few studies have been developed in the measurement of loading forces in shoes that are of untypical shapes and functions. Several studies deal with the measurement of the interactive force in downhill skiing (Virmavirta 2000, Lafontaine 1998, Lafontaine, 2001), cross-country skiing (Stoggl 2010), figure skating (Kho 1996), speed skating (Yuki 1996) and skating in ice hockey skates (Paersal 2001, Dewan 2004, Paersal 2010). Most of these studies were designed without a single subsequent follow-up. Measurement of loading forces on the sole of feet during ice-hockey skating is useful to improve skating technique. The output from this measurement system has many applications in predictive and protective biomechanics. The purpose of this study was to construct a functional measuring system which is able to detect the amplitude and dynamic course of the loading forces exerted on the soles of the feet during skating.

After critical review of studies addressing similar themes we designed skates capable of measurement. The measuring system consists of hockey skates, four pair of strain gauges, transmission equipment and software. To measure distribution of pressure forces on the soles of feet detection insoles (Footscan Insoles®) were used. A force plate (Kistler®) was also used for calibration.

As a result of the work is creation, validation and calibration of measuring equipment for detecting the loading forces exerted on the soles of the feet during ice hockey skating. This makes it possible to record loading forces, distribution of pressure on the sole of feet and the course of the center of pressure (COP). The creation of a measuring device applicable to any type of skate will require future research.

Key words: loading forces, ice-hockey skates, the distribution of pressure forces, sports engineering, biomechanics

INTRODUCTION

Discomfort in the use of ice-hockey skates is associated with the distribution of pressure forces on sole of the foot (Paersal 2004). Distribution of plantar pressures can be measured by detection inserts. It is more accurate to measure the amplitude of the loading forces on the beams on a blade holder, which is an integral part of skates. These works describe a calibration and functional verification process of the “measuring skate”. The model of the measuring skate is able to measure the amplitude and point of action of the loading force between the ice and skates (derivatively the load on the sole of the foot). Loading forces measurement during skating in ice-hockey may be used in practicing skating technique. The accuracy of this measurement system has many applications in predictive and protective biomechanics and sports engineering.

Research investigating the mechanics of ice skating has focused mainly on the general kinematics variables influential to performance (Lafontaine 2004, Jobs et al. 1990, Houdijk et al. 2000, DeBoer et al. 1987). However, the biomechanical parameters are not uniformly described. Consequently, the exact mechanics of force interaction between the skate and ice surface is not well known. The biomechanical characteristics of the foot during skating like distribution of pressure on the sole of the foot, the course of the COP and the amplitude of the loading forces exerted on the foot are not precisely defined. For their detection a very specific measuring device must be constructed.

The measurement of interaction (loading) forces with respect to hockey skates requires a different methodology than measurements in normal shoes. For the purpose of force detection it is not possible to use the force plate installed as the bedrock beneath the ice. That is because the contact of an ice skate with a surface is shattering the ice and not all components of the interaction forces are detected on the force plate. Thus we have to measure interaction forces on the actual skate. There are several basic methods of measuring the loading forces on skates. Basic equipment for detection is: piizometric sensors, pressure sensors and strain gauges. Most of the published studies on the ice-hockey skate use strain gauge (Yuki 1996, Paersal 2001, Dewan 2004, Paersal 2010). Strain gauges sensors have the advantage of easy placement on the skate blade holder with sufficient accuracy.

The “Ice Hockey research center” at McGill University in Montreal is the principal workplace regularly developing the methodology of measuring the loading forces during skating. This center is essentially the one place that is regularly engaged in publishing on this issue. This work brings an own technical solution for detection of loading forces acting on the sole of foot during skating.

OBJECTIVES

The aim of this study is to construct a functional measuring system which is able to detect the amplitude and dynamic course of the loading forces exerted on the soles of the feet during skating.

METHODS

The critical review of methods measuring plantar pressures and the amplitude of the interaction forces was done before the actual design of the measuring system. These reviews bring up the choices of measuring equipment which were used in the measuring system. Strain gauges were chosen as a detection device for the size of the loading force. Their application has been selected for other studies (Yuki 1996, Paersal 2001, Dewan 2004, Paersal 2010). Strain gauges used as a measuring device are sufficiently accurate and the application is not technologically challenging. For strain gauges it is important to choose an appropriate location for the placement on the skate and select the appropriate involvement in "Wheatstone bridges".

From the biomechanical point of view it is important to determine the loading force acting orthogonal on the sole of the skate. It is also possible to determine the bending (medio-lateral) force, but the strength of the loading effect of this force is negligible (Paersal 2010). Reference to **loading force** is meant as the force applied orthogonal to the sole of the skate. During skating the skate is flipped, while the slope of skate blade to the ice is dynamically changing. This is one of the reasons why it is necessary to measure the loading force on a beam above the blade.

Reference to bending force (medio-lateral force) is meant the force acting orthogonal to the line of the blade. Its share of the loading forces acting on the soles of the feet is negligible (Paersal 2010).

Strain gauges must be positioned at the place of the biggest compressive or tensile deformation of the skate blade holder, such place being just below the attachment of the beam on a shoe (Fig. 1). Because the skate blade is attached by two constructed beams to the shoe, the strain gauges must be placed on both of them. Overall, at least 4 pairs of strain gauges need to be involved for the detection two independent forces. Wheatstone bridges circuits are engaged for the **load of the front beam** and the **rear beam**. Pairs of strain gauges are connected into Wheatstone bridges to detect pressure-tension deformation (pressure and tension are antagonistic). The loading force is measured from a beams deformation due to compression or tensile.

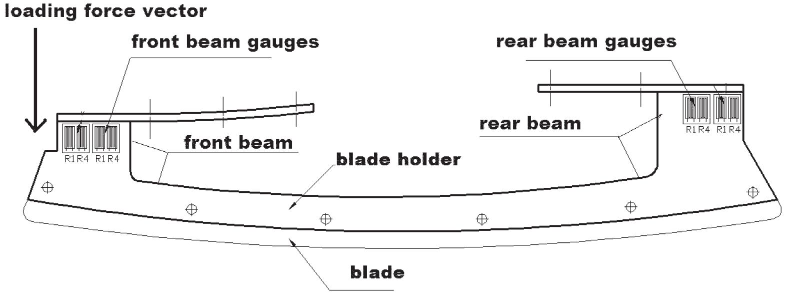

Figure 1. Placement the strain gauges on construction of blade holder. Strain gauges were adhered on both sides of the construction. One Wheatstone bridge circuit consiste of a 4 pieces of gauges. One circuit was used to detect the loading force on front beam and one on rear beam. The recorded signals indicated the compressive or tensile deformation of the skate blade holder between the skate boot and skate blade.

The location of strain gauges used (Fig. 1) allows a very important finding, this being information as to what force is transmitted on the front beam and what force on the rear beam. In addition is detected the point of loading force action on the blade of the skate. The construction used allows detection of relative loading forces transmitted to the front beam and rear beam simultaneously with location of force action on the blade. This information could be also evaluated simultaneously with the course of COP.

Distribution of loading forces on the sole of the foot and the course of COP are sufficiently accurate to measure by using existing facilities. For this detection was used measuring inserts "Footscan Insoles®".

Installation of strain gauges

The instrumentation system consisted of these main components: a hockey skate with strain gauges bonded to the blade holder, a portable data acquisition system, and post processing software to convert micro strain signals to force estimates.

The skate used was the Nike-Bauer Supreme 90 (left side only); four gauge sets (four strain-gauge sensors 6/350DK11E HBM), signal amplifiers (DEWETRON DAQP bridge B amplificity 0.1 mV/V), AD converter (NI-USD 6251-18bit) and the PC station with the evaluation software (Dewesoft original-software-DEWETRON). Strain gauges are connected to full bridge (see Fig. 2), from which the signal passes through the AD converter to a PC station. Data was collected immediately in acquisition software.

Structural adjustments of the measuring skate were done for the first construction. Those adjustments facilitated the initial measurement and analysis. Any modifications done to the skates did not affect the functionality of skates, but their real use can affect the locomotion of tested person. Any modifications made were not related to overall dimensions of the blade holder, but his partial geometry, mechanical properties and weight.

The following modifications were done on skate:

1 – Structure of blade holder was made of steel.
2 – Skate weight increased by 75%.
3 – Beam geometry was changed while maintaining the overall dimensions.

Blades holders are usually made of plastic to minimize the weight of the skates. In addition, the shape of the beam is usually conus in order to use as little construction material as possible. The typical holder shape is very demanding for computations, thus for the purposes of detecting force it would be necessary to use multiple sets of strain gauges.

There are two main reasons why the steel construction was used. The first reason was for the accurate detection of transiting forces. Steel material is a sufficiently sensitive and allowe the adhesion of strain gauges. The second reason was for the possibility of creating a simple shape of the blade holder, which allows for the easy quantification of the loading forces. For the future development of a measuring system it will be necessary to use a detection system applicable to normal shape of a blade holder.

Because steel was used, the weight of the skates (Bauer 90) was increased from 800 grams to 1400 grams (by 75%). Bauer 90 is one of the lightest models of skates. So the total mass of the measuring skate could match the common weight of skates. The

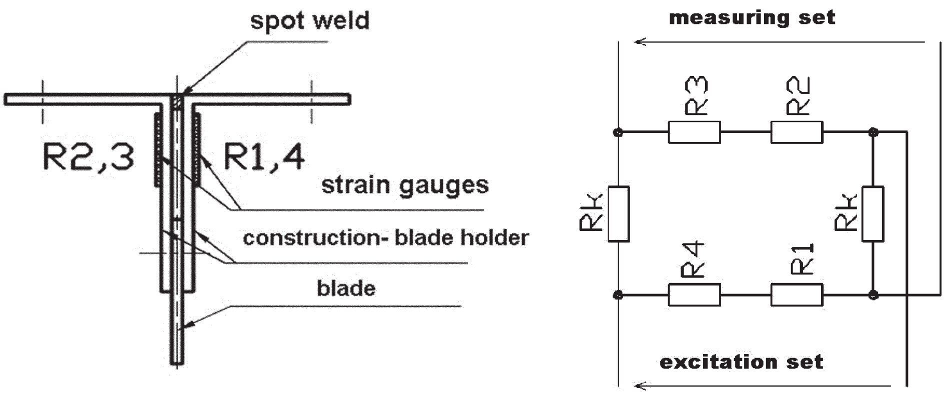

Figure 2. Left side: Side placement of strain gauges. Gauges were placed on both sides on construction of blade holder. Gauges made couples for wiring the into Wheatstone bridges. R1,4; R2,3 mean couple of strain gauges.
Right side: Scheme of wiring strain gauge into Wheatstone bridges for loading force. Arrows show excitation set and measuring block. R = resistance field, Rk = constant resistance, R1–R3 = gauges.

purpose of this study was developing an accurate measurement system without the actual evaluation of the skating technique. Therefore skate weight reduction was not needed.

The strain gauges were adhered at locations with the largest projected deformation of the blade holder in order to determine the loading forces acting between the ice and the hockey skate (Fig. 1 and 2). For detection one loading force was used two parallel gauges on both sides of the mounting beam structures on blade holder (Fig. 2). Beams were connected by a solid weld, which ensures the homogeneity of the measured area.

Figures 1 and 2 show the exact location of strain gauges on the blade holder. Pair of strain gauges are named according to their location. Front beam gauges and rear beam gauges were placed as close to soleof the skate as possible. Four sets of gauges were considered as a minimum quantity for accurate measurements, which allow validation of the measuring system.

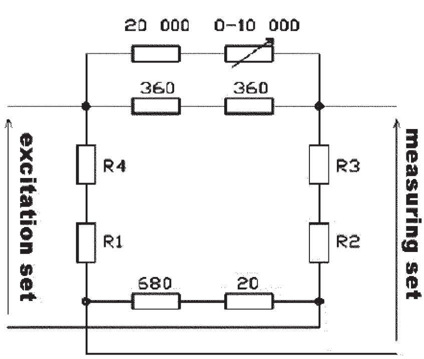

Figure 3. The wiring strain gauge into Wheatstone bridges circuit. Wiring is for loading and tensile force allowing mechanical balancing the bridges circuits. Arrows show excitation set and measuring block. R = resistance field. Figures are shown in Ohm (Ω).

A very important aspect was wiring gauges into Wheatstone bridges circuit (Fig. 2 and 3). The wiring of the gauges was done in a way allowing fine electronic and rough mechanical balance. This system facilitates the balancing process itself and also helps during validation process.

Calibration and Validation

Calibration and validation of the measuring equipment comprised the following points:
1 – Static calibration
2 – Determination of the calibration function of strain gauges
3 – Validation of detected values – loading forces
4 – Verification on field

First static calibration was performed on separate sets of strain gauges, and then follows the calibration involving both sets of strain gauges. The method of execution was loading the blade in the direction of the loading force by known weight on strict points. During calibration the front beam gauges the front part of the boot was fixed in gripper while the rear beam of the skate remained free. During calibration the rear beam gauges was back part of boot fixed in gripper while the front beam of skate remained free. After the calibration of the separate gauges was done the calibration of both sets of gauges together was done in the same way. Calibration was done for a constant loading force of 100, 200, 300 and 500 N. Used type of strain gauges (HBM 6/350DK11E) achieve the similar strain changes at a steady load and single impact. Static calibration functionally corresponds to the dynamic changes. Therefore it was not necessary to have to perform dynamic calibration. Calibration process was performed at 11 locations on the skate blade, and the calibrated distance of points was approximately 20 mm. Calibrated points on the skate blade were marked with zero point at the back of the rear beam and expressed in meters (m). Markers began at value 40 mm and ended at the value of 250 mm which is where the extreme positions are no longer involved in skating forward in contact with the ice. The same markers on the blade were also used in the validation of the measuring skate. Values of the electrical signals from the strain gauges were allocated to loading force and its position on the blade. The total size of the force was determined from the sum of signals from both sets of strain gauges (front beam signal PF + PR signal from rear beam). Location of loading force was determined by the ratio of signals (Equation 1, Fig. 4).

From the calibrated values of signals were detected the calibration function for the strain gauges and the ratio of signal to the point of action of the loading forces on the blade. From these functions were determined the relations between signal strength, amplitude of loading force and locations of location forces on the skate blade. Figures 4 and 5 show the function for determining the amplitude of loading force and function of signal strength with connection to point of action the force. The total loading force (F/N) is calculated from the sum of both signals (PF + PR) multiplied by the calibration factor (Cf). Calibration factor is also dependent (by its function – Fig. 5) to the point of action of loading force (s) (Equation 1).

$$F = Cf(s) \times (PF + PR) \tag{1}$$

Calibration curves are determining the calibration factor (Cf) and the mathematical function for calculation the point of the action the force. The Cf is determined by second-degree polynomial. This polynomial expresses the function of locations the loading force (m) to the ratio between signals from two sets of strain gauges and the load-bearing force (V/N).

The data from static calibration was used to estimate the CF, see table 1. The most important was calculation the point of action of loading force on the skate blade, s (Equation 2).

$$s = -0.0826\times\left(\frac{PF}{PR}\right)^4 + 0.1978\times\left(\frac{PF}{PR}\right)^3 + 0.1109\times\left(\frac{PF}{PR}\right)^2 + 0.1483\times\left(\frac{PF}{PR}\right) + 0.2336 \quad (2)$$

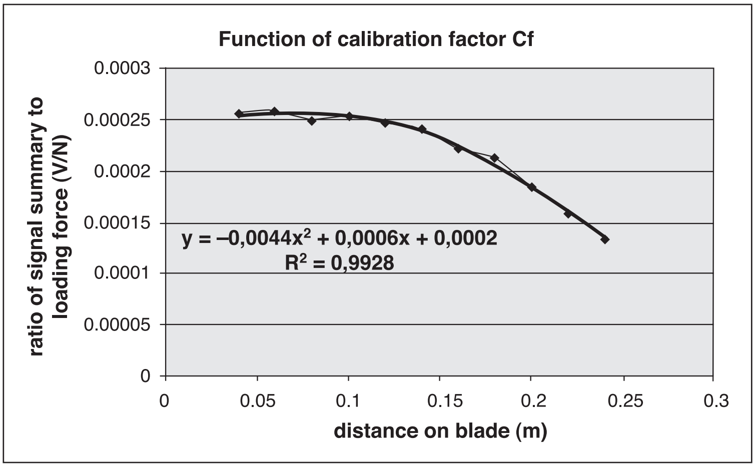

Figure 4. Function of calibration factor. The calibration factor depends on the point of action of the loading force on blade (s). Cf is calibrated as a function of summary signals from both sets of strain gauges (PF + PR) to distance of point of action on blade (m), R = resistance (′Ω).

Table 1. The data of a static calibration. The x means distance of calibrated point from zero location. PF = signal from gauges on front beam, PR = rear beam gauges signal, Cf = Calibration factor for loading force.

x	length ratio	PF+PR	PF/PR	Cf
(m)		(V)		(V/N)
0.04	0.13333333	0.117256	1.373117	0.000256
0.06	0.2	0.136037	1.228638	0.000259
0.08	0.26666667	0.149426	1.106469	0.000249
0.1	0.33333333	0.142802	0.897925	0.000253
0.12	0.4	0.151802	0.733006	0.000248
0.14	0.46666667	0.149767	0.567967	0.000241
0.16	0.53333333	0.138626	0.447889	0.000223
0.18	0.6	0.122947	0.321718	0.000212
0.2	0.66666667	0.096122	0.19902	0.000184
0.22	0.73333333	0.084916	0.095826	0.00016
0.24	0.8	0.075301	–0.04844	0.000133

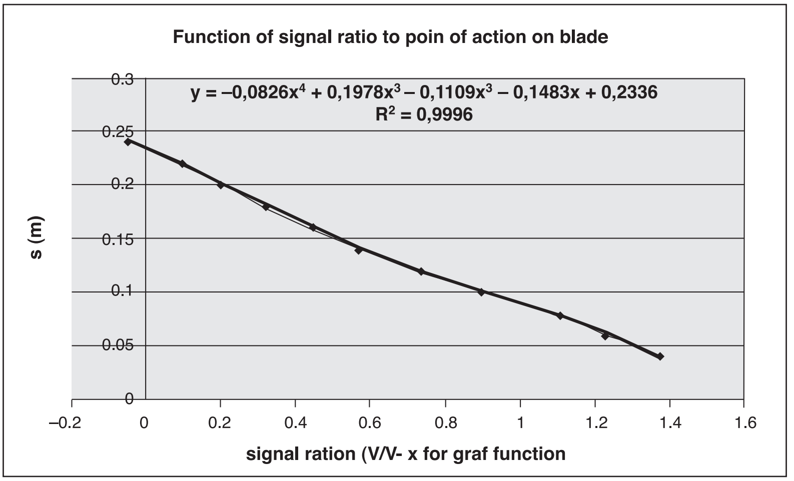

Figure 5. The dependency of signals ratio from strain gauges to the point of action of loading force. y = function of the dependence of force on her point of action, x = ratio of signals from strain gauges (V/V), R = resistance (′Ω).

After the calibration of the measuring skate and determination of the calibration function of loading force the validation process was performed using force plate – Kistler®. A skate measuring system was loaded at calibrated locations while the force plate was under the skate. Simultaneous record from the force plate and the measuring skate was the principal of validation. The skate was loaded by the weight of the person gradually to 11 statically calibrated locations of the skate blade and on two positions without a static calibration. Loading was done on the force plate with stabilization of the measured positions. The person was sitting on a chair, putting booted skate in different positions on the mounting point on the force plate. The stepping place was always pre-defined on blade with stabilizing the position of the foot. The size of the load was not clearly defined loading force caused by the person stepping on force plate and pushing knee in the vertical direction. The post processing software on the measuring skate has been working with dates calibrated by static calibration. The validation proces consisted of a comparison of output values from two different measuring devices. The standard value was the force plate. Comparison was done for the dynamic progress of the forces, the amplitude of the measured force and the force point of action on blade. Figure 6 shows the comparison of both measuring devices. The loading force values and the dynamic changes of the force from the measuring skate correspond to the same simultaneous record from the standardized force plate.

Bare data from measuring skate is the changes of voltage U (V). Static calibration provided the conversion of electric signal value to the amount of loading force. The value of loading force was assigned as the median of voltage readings. By comparing the force curve from the measuring skate to the second measuring device (force plate) the validity of readings was demonstrated. Force curves and their values are congruent. Correspondence was high except for one measured location. This point is the point during normal skating outside the contact area of ice skating blade. It is a point at which the loading force can

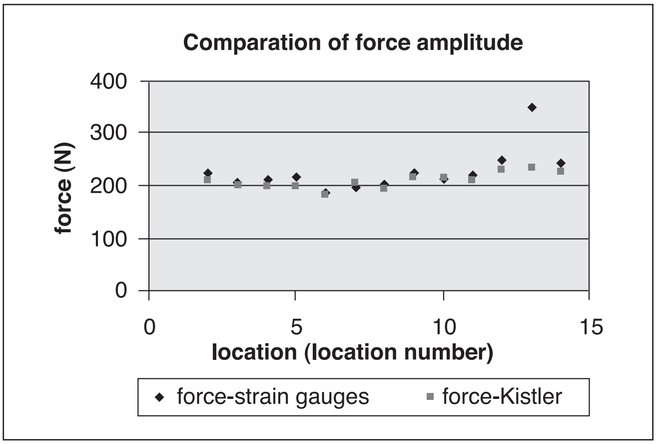

Figure 6. Comparison of measured forces by the strain gauges measuring skates and data from the force plate. Positions on the skate blade are expressed in location number of measured points. Only one force amplitude did not match the same amount on both measuring devices. This point is already located in the outskirts of the blade, which is not a conventional roller in contact with ice.

be revealed to the position of the two sets of strain gauges as a tension. Therefore this deviation in measurements is considered permissible.

A nonlinear function was created from the signals of strain gauges, from those functions it is possible to calculate the value of detected force. The calculated values were compared with the values from the force plate (for validation the result was from working with bare data, not software output).

Once validation had been carried out the first practical test of functioning of skate was done (verification). Practical test was performed on a “Skating belt” (skatemill) during forward skating. Verified functions were the data collection during real movement, display in post processing software and recording equipment. The same test was the carried out on the ice. On ice testing provided in addition to measuring skates the measuring insoles device.

The outcome of these tests showed that the actual measuring devices and data collection is functional. Now it is possible to begin with identifying the optimal range of measured forces and measurement tolerance. Synchronization of the two measuring devices, the measuring skate and the Footscan Insoles® is possible from the timeline of the two devices.

The measuring insert (Footscan Insoles®) was chosen for the measuring of the distribution of pressure forces on the sole of the foot. This device detects the proportional distribution of pressure forces and the course of the center of pressure forces (COP) on the sole of the foot. This device has sensing frequency 500 Hz (recorded every 20 ms) and the output of the measuring insert can be time-synchronized with the measuring skate.

The practical test showed the timeline possibility of the synchronization of the measuring skate and the measuring insert. The Footscan Insoles® device allows graphical and numerical output. For the COP course graphic output is generally used (Fig. 7), which is possible in any time period with current evaluation the distribution of pressure forces.

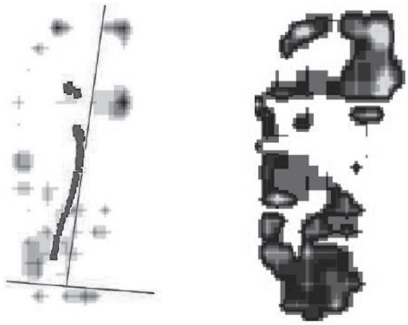

Figure 7. Left side show the graphic output from Footscan Insole. Recorded feature is tracking the COP in take off phase during forward skating. Right picture is summary of pressure distribution during the take off phase. The data is collected under sole of the foot.

RESULTS

The vertical loading tests yielded correlations of the voltage reading (strain gauge) to force (measured on the force plate). The measuring system created is able to detect the amount of loading forces on the skate and its point of action. Together with the Footscan Insoles® system it is possible to determine the distribution of pressure forces on the feet as well. The functionality of this system was verified on ice. The time-synchronization of the measuring skate with Footscan Insoles® was practically approved.

The designed measuring device – "measuring skates" was calibrated to the force of 100, 200, 300 and 500 N. From calibrated values was detrmined the calibration factor. This allows the calculation of loading force for any load value. Design allows free movement of the hockey player in a 35 meter track. Measurement of loading forces on the skate blade holder is possible with a sensitivity of between 0.1 and 2000 N.

The measuring system is able to detect the interaction forces between the ice and the hockey skate with the current record of the distribution of pressure forces on the feet together with the record a dynamic course of the COP. This measuring system has original construction with own possilbilities of evaluation the outputs.

DISCUSSION

A result of the work is the creation, validation and calibration of measuring equipment for detecting the loading forces exerted on the soles of feet during ice hockey skating. However, it is a prototype device that must be to developed for practical use. The same kind of measurement system is published only in a study from McGill University, Canada (Paersal 2010). This study used a similar measurement principle with different output. In the Paersal study, a technology of strain gauges adhered to the skate blade holder was also used. However, this device is not able to detect the ratio of forces acting on the front and rear beams of the skate blade holder. Advatages of Paersal device is application on any kind of skates. Paersal device is using only a single strain gauge for detecting loading force, which is by itself a disadvantage for the locations of point of action the loading force. Our study shows that the currently used system can be qualitatively improved.

For practical it is necessary to always make the perfect compromise between detection and applicability in the field. Now is not clear how accurate the device have to be for detection of pressure forces in practical use. Therefore, the study was directed to achieve the most accurate detection of pressure forces. Only after a high number of measurements on model skate will be possible to adjust accuracy for practical use.

The location of strain gauges in this work is similar to a study of Yuki (1996). This location of strain gauges achieves the greatest possibility of the detection of the loading forces on ice-hockey skates. Either way, the original involvement of the strain gauges for detection of loading forces on two beams on the skate holder while this device is detecting point of action the loading force on the blade of skate. The validation proces of created device was not proved only at one measured point. This point is located in the outskirts of the blade, not at conventional roller in contact with ice. It is a point at which the loading force can act for strain gauges as a tension. In essence, this is another advantage of using strain gauges. If we are measuring the homogeneous system of skating boot and blades, the load on one side of the device produce a force of opposite direction (tension) of other part. This effect is eliminated during post processing calculation. The system include a particular variation of the signal from a front beam gauge and back beam gauge.

A very important skill of this device is the possibility of time synchronization of the measuring skates with the measuring insert (Footscan Insoles®). The Insoles measuring system accurately detects a distribution of pressure force, but is unable to accurately detect an amplitude of the interaction forces on the sole of the foot (Chen 1994). In this study, accurate detection of pressure forces on the sole of the foot with their amplitude and detection the point of action of loading force on the blade is linked. This is first such complex system for detecting interactive forces on ice-hockey skate.

CONCLUSION

The measuring system is able to detect the interaction forces between the ice and the hockey skate with the current record of the distribution of pressure forces on the feet together with a dynamic course the record of the COP. This measuring system has original construction with own possilbilities of evaluation the outputs.

This system is only a test case solution. For practical applications a system of strain gauge placement on any type of skate would have to be developed. The use of strain gauges is the same on the metal and plastic material. The issue of the location of strain gauges on the typical shape of the blade holder remains slightly problematical.

The results of this study are used in the learning process at the Faculty of Physical Education and Sport.

List of abbreviations

COP – center of pressure on the sole of foot
PF – pressure front, gauges set detecting front beam pressure
PR – rear pressure, gauges set detecting rear beam pressure
s – factor for determining the position of the skate blade
R – Resistance
Cf – calibration factor

ACKNOWLEDGEMENTS

This paper has been supported by the GAČR P 407/10/1624 grant, GAUK 111 310 grant and SVV-2010-261602 grant.

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DETEKCE ZÁTĚŽOVÝCH SIL PŮSOBÍCÍCH NA BRUSLE A CHODIDLA PŘI BRUSLENÍ

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SOUHRN

Měření zátěžových sil působících na nohu je dlouhodobě prováděno u běžných pohybů jako chůze, běh, skoky a další. Pro tyto pohyby bylo uskutečněno mnoho měření jak naboso, tak s využitím obuvi (Klenerman, Wood 2006, Meldrum, Hilton 2004). Podstatně méně jsou rozvinuta témata měření zátěžových sil u obuvi netypických tvarů a funkcí. Několik studií se zabývá měřením těchto sil ve sjezdovém lyžování (Virmavirta 2000, Lafontaine 1998, Lamontaine 2001), běžeckém lyžování (Stoggl 2010), krasobruslení (Kho 1996), rychlobruslení (Yuki 1996) a bruslení v ledním hokeji (Paersal 2001, Dewan 2004, Paersal 2010). Většina z těchto studií je koncipována jednorázově bez longitudiální návaznosti.

Měření tlakových sil na plosce nohy během bruslení v LH může být využito v tréninku techniky bruslení, prediktivní a protektivní biomechanice. Výhledovým využitím je i výzkum příčin diskomfortu při používání hokejových bruslí a dále ve sportinženýringu. Cílem práce je vytvořit funkční měřící systém, který je schopen detekovat velikost a dynamický průběh zátěžových sil působících na bruslařskou botu a plosku nohy během bruslení.

Po kvalitativní analýze formou kritického review studií řešících obdobnou tématiku byl navržen model „měřící brusle“. Měřící systém se skládá z hokejové brusle, čtyř párů tenzometrů, přenosového zařízení a softwaru. Pro měření distribuce tlakových sil na plosce nohy bylo využito detekčních vložek do bot (Footscan Insoles®). Pro kalibraci byla dále využita dynamometrická deska (Kistler).

Jako výsledek práce byla zkonstruována, kalibrována a validována měřicí aparatura pro detekci zátěžových sil působících na bruslařskou botu a dále byla použita technologie *Footscan Insole* pro detekci tlakového pole mezi plosku nohy a botou a trajektorií COP. Pro přímou aplikaci a praktická měření je zapotřebí vytvořit detekční zařízení aplikovatelné na jakýkoliv typ brusle.

Výsledky této studie jsou využívány v pedagogickém procesu na FTVS UK Praha.

Klíčová slova: zátěžové síly, hokejová brusle, ploska nohy, distribuce tlakových sil, sportinženýring, biomechanika

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