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CLOSED KINEMATIC CHAIN ANALYSIS IN ATHLETES’ START PERFORMANCE AT A SLIDING TRACK

Summary of the Doctoral Thesis

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GENERAL DESCRIPTION

The essence and relevance of a problem

Sports that involve a relatively small number of athletes usually also attract less scientific studies, and as a result, understanding of underlying principles in these sports is often inhibited and incomplete. The sliding sports – bobsleigh, skeleton and luging, can be considered belonging to this category, since there are just hundreds of athletes all over the world practicing these sports. A limited number of athletes apparently is not the only reason for a restricted amount of published studies. Taking into account the tough competition between the major represented countries, and a constant improvement of athletic results, there are reasons to believe that there is a significant amount of scientific work on-going in the field of the sliding sports, but not all the results become broadly published. [4]

In technical sports, which also include the sliding sports, the results depend both on athletes' conditioning and skills and on the suitability of equipment to a given environment. Considering the sleds, there are two major research fields – improvement of aerodynamic properties and reduction of friction between the blades and ice. Findings of these studies are often balancing on the edge of rule violation, and seldom are shared with competitors. Conditioning and elaboration of athletic skills within the training process is another way of advancing the results. Evaluation and understanding of individual specifics is essential in improvement of the training program at the highest athletic level, and this, in turn, requires a thorough analysis of underlying biomechanical and physiological processes.

In Latvia all the sliding sports has been developing very successful and so far are the most promising among all winter sports. Latvian national team expectations for the major athletic event – the Olympic Games – are mainly put on sliding sports. Excellent results have been already achieved, including three Olympic medals during the last two Olympic Games, medals at the World Championships and the World Cups. Tough competition between the participating nations requires constant improvement in athletes' training and competitive efficiency. Kinematic and kinetic analysis is a step towards better understanding of athletic technique particularities in sliding sports, which is a priority research area both for the top-athletes and youth team candidates.

The Objective and Tasks of the Research

The **objective** of the research is to refine the analysis method of athlete-and-sled closed kinetic chain performance and to adapt it for use in improvement of elite athletes' training feedback quality.

With regard of the objective, the following tasks are defined:

- to develop a computer model of athlete-and-sled kinematic chain in order to assess lugers' individual start kinematics and kinetics;
- to develop a visualization model of luge start in order to simulate the athletes' performed and computer-calculated start movements;
- to develop and validate a calibration procedure applicable in athletes' training and competitive environment, which simplifies the motion capture procedure without impairing the precision of reconstructed coordinates;
- to evaluate in terms of timing lugers start performance at Sigulda track and start ramp.

Scientific Novelty of the Research

For the first time a computer simulation model of luge start was developed. The necessary model segments and degrees of freedom for accurate movement simulation were theoretically determined. Correlation between start and finish times at Sigulda luging track, as well as influence of the initial start phases on the total start time were evaluated. It has been shown that the horizontal velocities of athlete's and sled's centres of masses differ in the initial start phases.

Practical Importance of the Research

The developed computer model of luge start allows evaluation of kinematics and kinetics of athletes' performed movements, as well as prediction of these parameters for theoretically modified movements. The developed calibration procedure together with the visualization model considerably improves motion capture practical application in athletes' training and competitive environment. The computer model of the start ramp allows adjustment of this calibration procedure for skeleton and bobsleigh starts.

Approbation of the Research Results:

The main results of the research are presented in the following publications (5, 7, 8, 9, 11, 12, 14, 15, 16 and 17) and conference abstracts (1, 2, 3, 4, 6, 10 and 13):

1. Fedotova V., Pilipiv V. Simplified Planar Kinematic Chain Model of Initial Start Phases in Luging. Abstracts of the 17th annual Congress of the European College of Sport Science (ECSS), Bruges, Belgium; July 4-7th, 2012, 561.
2. Fedotova V., Pilipiv V. Power Production during the Initial Phases in Luging: a Preliminary Study. Abstracts of the 17th annual Congress of the European College of Sport Science (ECSS), Bruges, Belgium; July 4-7th, 2012, 340.
3. Fedotova V., Pilipiv V. Computer Modelling in Sport Movement Analysis – Simplification of Model Drivers. Abstracts of the 5th Baltic Sport Science Conference "Current Issues and New Ideas in Sport Science", Kaunas, Lithuania; April 18-19th, 2012, 65.
4. Fedotova V., Pilipiv V. 3D Camera Calibration for Motion Tracking in Recurrent Athletic Environment. Abstracts of the 5th Baltic Sport Science Conference "Current Issues and New Ideas in Sport Science", Kaunas, Lithuania; April 18-19th, 2012, 64.
5. Fedotova V., Pilipivs V. Variability of Timing Parameters of Starts Performed by Lugers with Different Competitive Experience. Scientific Materials, 2011, 13, 419–427.
6. Fedotova V., Pilipiv V. Comparison of lugers' start elements on a sliding track and an iced start ramp. In: Soares S., Sousa F., Veloso A., Vilas-Boas J.P. (Eds.), Programme and Abstracts Book of the 29th Conference of the International Society of Biomechanics in Sports, Porto, Portugal; June 27th – July 1st, 2011, 136.
7. Fedotova V., Pilipiv V. Comparison of lugers' start elements on a sliding track and an iced start ramp. In: Vilas-Boas J.P., Machado L., Wangdo K., Veloso A. (Eds.), Portuguese Journal of Sport Sciences, 2011, 11(Suppl. 2), 223–226.
8. Fedotova V., Pilipiv V. Timing Rhythm in Female Lugers' Starts. Acta Kinesiologiae Universitatis Tartuensis, 2011, 16(supplement), 80.

9. Fedotova V., Pilipiv V. Comparison of Bobsleigh Performance at St. Moritz Track. Acta Kinesiologiae Universitatis Tartuensis, 2011, 16(supplement), 79-80.
10. Fedotova V., Pilipivs V. Variability of Timing Parameters of Starts Performed by Lugers with Different Competitive Experience. Book of abstracts of the XV International Conference “Physical Activity of People at Different Age”, Szczecin, Poland; December 2-3rd, 2010, 23.
11. Fedotova V., Pilipiv V. Timing characteristics of female lugers’ starts on iced start ramp. Вісник Чернігівського державного педагогічного університету. Педагогічні науки. Фізичне виховання та спорт, 2010, 81, 679–682.
12. Fedotova V. Influence of Track Interval Times on the Total Run Time in Skeleton and the Sport of Luge. Sport Science (Sporto Mokslas), 2010, 3(61), 47–55.
13. Fedotova V., Pilipivs V. Biomechanical Patterns of Starting Technique during Training and Competitive Events for Junior Lugers. Book of Abstracts of the 6th World Biomechanics Congress, Singapore; August 2-6th, 2010, 88.
14. Fedotova V., Pilipivs V. Biomechanical Patterns of Starting Technique during Training and Competitive Events for Junior Lugers. IFMBE Proceedings, 2010, 31, 282–285.
15. Федотова В.А., Пилипив В.М. Наглядное представление данных в мультимедийных методических пособиях для спортсменов и тренеров. Материалы международной научно-практической конференции «Информационное пространство современной науки», Чебоксары, Российская Федерация; 6 февраля, 2010, 171–174.
16. Федотова В.А., Пилипив В.М. Использование программного обеспечения удаленного доступа для реализации анализа движения спортсменов в условиях учебно-тренировочных сборов. Материалы международной научно-практической конференции «Актуальные проблемы физической культуры и спорта», Чебоксары, Российская Федерация; 10 декабря, 2009, 217–220.
17. Fedotova V., Pilipiv V. Preparing Video-Based Teaching Aids for Elite Athletes: Software Choice. V Jauno zinātnieku konferences rakstu krājums, Rīga, Latvija; 2009. gada 2. decembris, 32–39.

The results of the research have been reported at the following local and international conferences:

1. Fedotova V., Pilipiv V. Simplified Planar Kinematic Chain Model of Initial Start Phases in Luging. The 17th annual Congress of the European College of Sport Science (ECSS), Bruges, Belgium, July 4-7th, 2012. Abstract book page No 561.
2. Fedotova V., Pilipiv V. Power Production during the Initial Phases in Luging: a Preliminary Study. The 17th annual Congress of the European College of Sport Science (ECSS), Bruges, Belgium, July 4-7th, 2012. Abstract book page No 340.
3. Fedotova V., Pilipiv V. Computer Modelling in Sport Movement Analysis – Simplification of Model Drivers. The 5th Baltic Sport Science Conference "Current Issues and New Ideas in Sport Science", Kaunas, Lithuania, April 18-19th, 2012. Abstract book page No. 65.
4. Fedotova V., Pilipiv V. 3D Camera Calibration for Motion Tracking in Recurrent Athletic Environment. The 5th Baltic Sport Science Conference "Current Issues and New Ideas in Sport Science", Kaunas, Lithuania; April 18 – 19th, 2012. Abstract book page No. 64.
5. Fedotova V., Pilipivs V. Latvian Olympic Team – a practical experience in Motion Capture. International Symposia „Sports Science in Elite Sports: Putting Theory into Practice", Leuven, Belgium, September 12-15th, 2011.
6. Fedotova V., Pilipiv V. Comparison of lugers' start elements on a sliding track and an iced start ramp. The 29th Conference of the International Society of Biomechanics in Sports, Porto, Portugal, June 27th – July 1st, 2011. Abstract book page No. 136.
7. Fedotova V., Pilipiv V. Timing Rhythm in Female Lugers' Starts. The 4th Baltic Sport Science Conference, Tartu, Estonia, April 7-9th, 2011.
8. Fedotova V., Pilipiv V. Comparison of Bobsleigh Performance at St. Moritz Track. The 4th Baltic Sport Science Conference, Tartu, Estonia, April 7-9th, 2011.

9. Fedotova V., Pilipivs V. Variability of Timing Parameters of Starts Performed by Lugers with Different Competitive Experience. The 15th International Conference "Physical Activity of People at Different Age", Szczecin-Malkocin, Poland, December 2-3rd, 2010. Abstract book page No. 23.
10. Fedotova V., Pilipiv V. Timing characteristics of female lugers' starts on iced start ramp. The 3rd International scientific conference in honour of A.Laputin "Present day issues of modern biomechanics of physical training and sports", Chernihiv, Ukraine, October 21-22nd, 2010.
11. Fedotova V., Pilipivs V. Biomechanical Patterns of Starting Technique during Training and Competitive Events for Junior Lugers. The 6th World Biomechanics Congress, Singapore, August 2-6th, 2010. Abstract book page No. 88.
12. Федотова В.А., Пилипив В.М. Наглядное представление данных в мультимедийных методических пособиях для спортсменов и тренеров. Международная научно-практическая конференция «Информационное пространство современной науки», Чебоксары, Российская Федерация, 6 февраля, 2010.
13. Федотова В.А., Пилипив В.М. Использование программного обеспечения удаленного доступа для реализации анализа движения спортсменов в условиях учебно-тренировочных сборов. Международная научно-практическая конференция «Актуальные проблемы физической культуры и спорта», Чебоксары, Российская Федерация, 10 декабря, 2009.
14. Fedotova V., Pilipiv V. Preparing Video-Based Teaching Aids for Elite Athletes: Software Choice. V Starptautiskā jauno zinātnieku konference, Rīga, Latvija, 2009. gada 2. decembris.

LITERATURE REVIEW

The literature review includes four chapters. In the first chapter a general description of bobsleigh, skeleton and the sport of luge (the sliding sports) is provided along with the current research analysis and the summary of scientific findings in these sports that are available in literature from 1978 till 2011. The sport of luge differs from the other sliding sports due to its particular start technique in a sitting position, therefore a detailed description of this technique is provided. The second chapter is dedicated to the concept of the kinematic chains in biomechanics of sports. In the third chapter application of motion capture technique in sports biomechanics, often used to assess performance kinematics, is discussed, including coordinates' reconstruction procedure from video records. The fourth chapter contains information on computer modelling and mass-inertia properties calculation techniques in sports biomechanics. The computer modelling is most commonly used to address the Forward and Inverse Dynamics problem, as well as to visualize and optimize an athletic movement. Kinematically-driven models are often built as a starting point in calculation of involved forces and torques.

The general conclusion of the analysed scientific studies is that in all sliding sports the start time is a prerequisite for a successful outcome of the run. [1, 6] Start time improvement appears to be a perspective way to the total growth of results in all sliding sports. Even a small advantage during the start can lead to a higher ranking at finish. In skeleton and bobsleigh the start performance is close to a sprint run. According to Sands et al., in skeleton start top athletes can reach up to 70 - 85% of their speed in regular 30 m sprint. These considerations generally define the content of the start trainings in skeleton and bobsleigh. [5] Due to its specifics, it is difficult to compare the start in the sport of luge to any other better studied sports, and the studies in luging itself are scarce. It had been reported, that the initial start phases in luge are essential for an outstanding start time, however, other biomechanical characteristics of the start are not available from literature. [2, 4] Assessment and analysis of kinematics and kinetics of the start is of an utmost interest from the prospective of mastering the start technique, and computer modelling appears to be one of the most appropriate methodologies to address this issue.

EXPERIMENTAL PART

The main research methods applied throughout the work were digital motion capture and computer modelling.

The following equipment and software was used in the research:

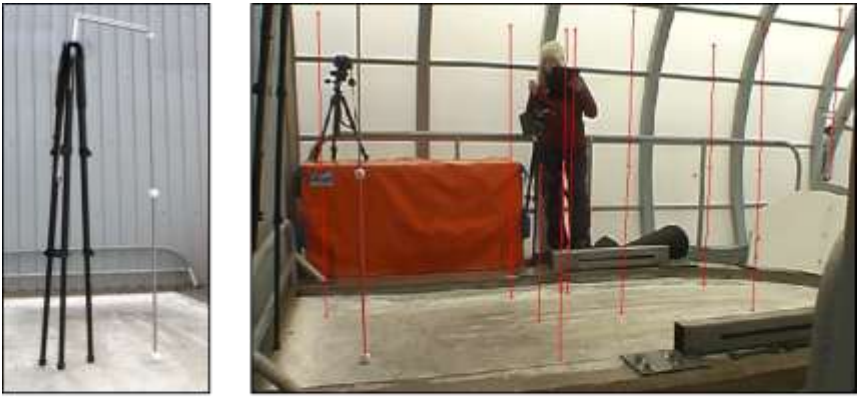
- time measurement at the start ramp was performed with the laser timing system Brower and the digital photo camera Casio EX-FH20 at a high-speed video mode (210 frames per second);
- motion capture was done with Simi Motion analysis system hardware and software;
- video records were captured with two high-speed video cameras Basler A602fc and one digital camera Sony DCR-HC96E, equipped with a wide-angle lens Sony VCL-HA07A;
- standard camera calibration procedure was performed with Simi Motion laser calibration system;
- additional video records needed for reconstruction of the start ramp computer model were performed with Samsung VP-D102D, Sony HDR_XR350VE and Panasonic HDC-TM700K digital cameras;
- the kinematically-driven computer model was developed using SimMechanics modelling environment of Simulink software;
- the start ramp model and the visualization model were created in Autodesk 3ds Max software.

Calibration of the Cameras

The start in the sport of luge is a complex movement, the body segments of an athlete are moving in multiple planes simultaneously, and planar coordinates of the joints cannot provide enough information for a satisfactory kinematic analysis. Reconstruction of spatial coordinates is only possible if the video cameras are calibrated for 3D calculations.

The standard calibration of the cameras was performed in accordance with the requirements of Simi Motion analysis system manufacturer. The procedure includes two main parts: videotaping of the calibration frame and processing of the obtained video records in Simi Motion software 3D calibration module; it is described in more detail below.

All the cameras used for the motion capture shall be synchronized.



(a) (b)

Figure 1. Calibration frame (a) and mapping of calibration points in a video record frame (b)

The calibration frame (Figure 1 (a)) is videotaped in at least four positions on the start ramp. All positions are measured with a distance measurer and an angle sensor, and registered in a calibration sheet. The distance from the ground to the lower marker on the calibration frame shall remain constant throughout the calibration procedure, which is difficult to achieve on a non-even surface of the start ramp. The calibration video record shall be continuous in order to be used in Simi Motion 3D calibration module, and the resulting video files from each camera often exceed 10 GB, which requires a considerable hard drive space for data storage.

Data from the calibration sheet are used in Simi Motion 3D calibration module to obtain spatial coordinates of the calibration frame markers. When this step is completed, the markers are mapped in the video records, and the respective 3D coordinates are assigned to each marker (Figure 1 (b)). These data are then used to calculate calibration parameters of the cameras, and the calibration parameters are, in turn, assigned to all motion video records captured with a corresponding camera. Combining in Simi Motion software several synchronous video records captured with calibrated cameras allows obtaining the spatial coordinates of the body landmarks during a start attempt.

To increase effectiveness of calibration in competitive environment a new procedure, based on a computer model of the ramp, was developed.

The 3D computer model of the start ramp was reconstructed in Autodesk 3ds Max software from multiple video records and measurements of the ramp. Spherical objects with known spatial coordinates of the centres were constructed in the model in order to mimic the calibration markers (Figure 2 (a)). In the new calibration procedure instead of the calibration video records the athletes' motion video records overlaid with the corresponding projections of the ramp model and the spherical objects are used (Figure 2 (b) and (c)). Initial data on camera positioning (up to several centimetres) facilitate agreement of the video record and the model planes. The overlaid video record saved as a single file can be processed in Simi Motion 3D calibration module the same way as the calibration video record in the standard calibration procedure–instead of the calibration frame markers the spherical virtual objects are mapped in video records and the spatial coordinates are assigned to these "virtual markers".

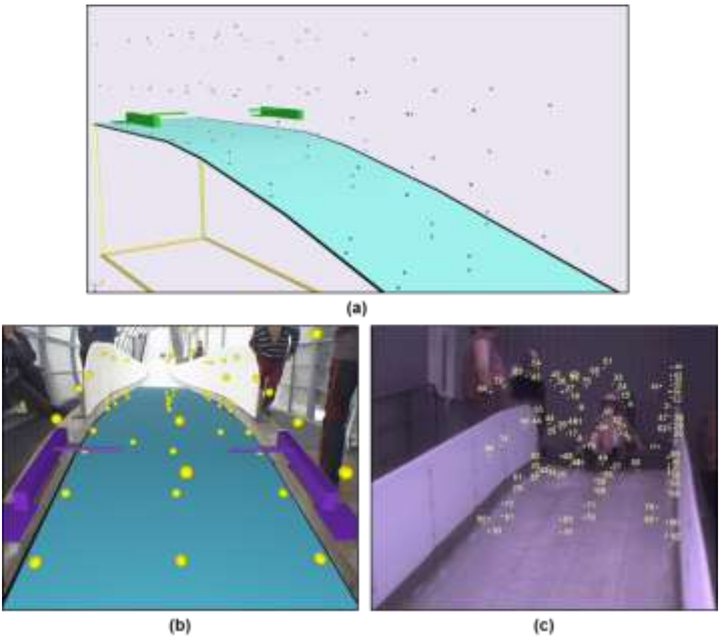


Figure 2. Model of the start ramp with „virtual markers" cloud (a); video record overlaid with the model of the ramp (b), and a video record frame with the „markers", ready for calibration

The new procedure eliminates the necessity to capture the calibration video records, and therefore is more effective in training and competitive environment. The computer processing procedure is the same as in the standard procedure, but an overlay operation of the model and the video record is added.

Motion Capture

The main goal of motion capture was to obtain kinematics of an athlete's body landmarks in order to create a kinematically-driven computer model. During the motion capture the synchronous video records of a start attempt were captured with several cameras and then processed in Simi Motion software. To reconstruct 3D coordinates, the necessary body landmarks shall be mapped in at least two synchronous video records from calibrated cameras. The following body landmarks were used in this work: vertex (Vert), acromion (Acr), epicondylus lateralis (Cub), processus styloideus ulnae (Man), articulatio coxae (Cox), condylus lateralis (Con), malleolus lateralis (Mal) and vertebra prominens (C7) – Figure 3. Kinematics of the sled was described with and additional point SLb – centre of the left runner of the sled.

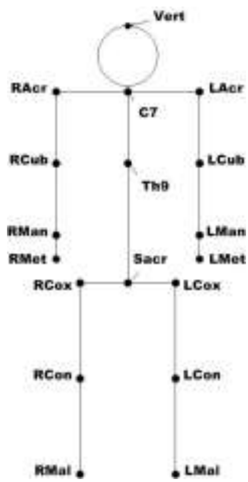


Figure 3. Placement of body landmarks

RMet, LMet (right and left 3rd metacarpal), Sacr (sacrum) and Th9 points were not mapped in motion capture procedure, but were used in the computer model as additional joints.

The estimated 3D coordinates reconstruction accuracy after smoothing with quintic splines method is ± 0.02 m.

Computer Modelling

The developed human body computer model, including the local coordinate systems of the segments, is based on Zatsiorsky et al. segment inertia parameters estimation model adjusted by de Leva. [3] The model in the research was developed for one athlete, using athlete's individual anthropometric measures and motion capture results. Estimation of necessary degrees of freedom (DOF) was done on the basis of motion capture results analysis for all 8 participants of the study. Anthropometric data of all participants of the study are shown in Table 1 (athletes A un B (juniors) – female, athletes C (junior) un D – male).

Table 1

Anthropometric data of the participants of the study

Athlete:	A1	A2	B1	B2	C	D1	D2	D3
Body mass, kg	86.6	73.1	73.7	69.1	86.8	81.9	89.3	88.7
Body height, m	1.74	1.73	1.75	1.70	1.91	1.84	1.76	1.83
Torso length, m	0.56	0.61	0.62	0.53	0.66	0.64	0.61	0.63
Thigh length, m	0.39	0.40	0.41	0.45	0.47	0.40	0.39	0.44
Shank length, m	0.41	0.42	0.39	0.33	0.48	0.42	0.40	0.43
Upper arm length, m	0.25	0.28	0.26	0.27	0.30	0.27	0.27	0.28
Forearm length, m	0.24	0.26	0.25	0.,23	0.29	0.26	0.26	0.27

The table presents lengths of the right arm and leg segments, as the body is considered symmetric

The length of the segments is measured between the body landmarks shown at Figure 3.

Analysis of kinematic chains was done using Machine and Mechanism Theory methods.

The developed computer model includes two start phases of the sport of luge, which are considered in literature as the most important phases [2]:

phase II – backward movement of the sled before the start spurt, or jerk, (the „compression” phase);

phase III – the start spurt, or jerk (Figure 4).

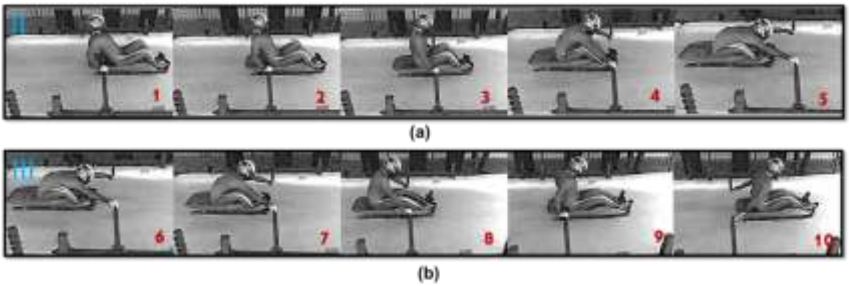


Figure 4. Movement sequence of start phases II (a) and III (b) in the sport of luge

RESULTS AND DISCUSSION

The kinematically-driven simulation model and visualization model of the main start phases in the sport of luge has been developed. New camera calibration procedure, which increases effectiveness of motion capture in training and competitive environment, has been developed and validated.

Validation of the Calibration Procedure

To validate the new procedure, two sets of 3D coordinates of reference objects were compared – the coordinates reconstructed with the standard and the new method. In addition, external dimensions of the objects were compared with the results of tape-measurements. Besides the static coordinates, the time-dependent functions of athletes' body landmarks coordinates, obtained during motion capture, were compared. The examples of the comparison results are presented in Figure 5, Table 2 and 3. Comparison of the reference object coordinates and the time-dependent functions had shown that both calibration procedures give the same values of coordinates within the measurement error. Reconstructed dimensions of the reference objects correspond to the real dimensions of these objects obtained by tape measure.

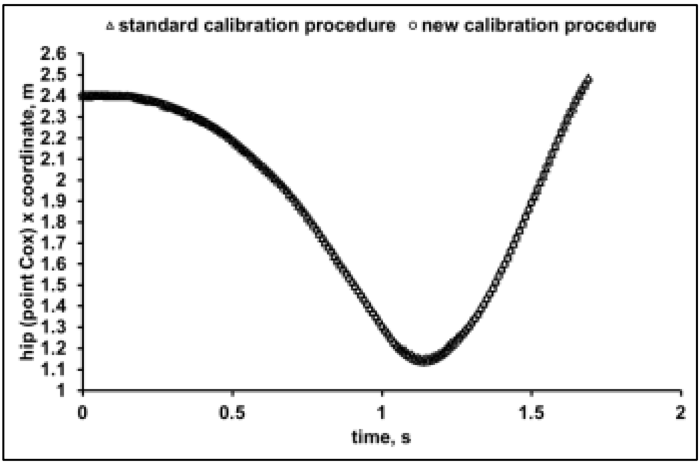


Figure 5. Comparison of calibration procedures – hip (point Cox) x coordinate time dependence

Table 2

Comparison of calibration procedures – 3D coordinates of the points

No.	Standard calibration procedure			New calibration procedure		
	x, mm	y, mm	z, mm	x, mm	y, mm	z, mm
1	567 ± 1	17 ± 1	56 ± 1	569 ± 1	17 ± 1	54 ± 1
2	1234 ± 2	1538 ± 2	467 ± 1	1235 ± 1	1539 ± 1	466 ± 2
3	2340 ± 1	194 ± 2	155 ± 2	2336 ± 1	194 ± 2	156 ± 1
4	2418 ± 1	12 ± 2	264 ± 1	2413 ± 2	6 ± 1	260 ± 2
5	2413 ± 2	148 ± 1	264 ± 1	2417 ± 3	147 ± 2	264 ± 1
6	2647 ± 2	1609 ± 1	589 ± 2	2645 ± 1	1610 ± 2	587 ± 1
7	3838 ± 1	71 ± 1	257 ± 3	3837 ± 1	68 ± 1	256 ± 1
8	4263 ± 3	267 ± 1	786 ± 1	4265 ± 2	267 ± 1	788 ± 1
9	4500 ± 1	456 ± 1	56 ± 1	4498 ± 2	455 ± 1	57 ± 1
10	5623 ± 2	782 ± 2	316 ± 1	5626 ± 1	782 ± 1	314 ± 2

Table 3

Comparison of calibration procedures – measurements of the reference object dimensions

	Standard calibration procedure	New calibration procedure	Tape measurements
Object 1 – length, mm	848 ± 2	851 ± 1	850 ± 1
Object 1 – width, mm	703 ± 1	702 ± 2	700 ± 1
Object 1 – height, mm	122 ± 1	120 ± 2	120 ± 1
Object 2 – length, mm	299 ± 2	297 ± 1	298 ± 1
Object 2 – width, mm	700 ± 1	702 ± 2	702 ± 1
Object 2 – height, mm	1539 ± 1	1540 ± 1	1541 ± 1
Object 3 – length, mm	297 ± 1	295 ± 2	298 ± 1
Object 3 – width, mm	1570 ±1	1569 ± 1	1570 ± 1
Object 3 – height, mm	404 ± 2	405 ± 1	405 ± 1

The tables show average values ± Standard deviation

The comparison results demonstrate that the developed new calibration procedure is suitable for accurate 3D coordinates reconstruction in athletes' training environment. Main drawback of the developed procedure is requirement of specialized 3D modelling software.

Time Measurements

Correlation analysis of the start and finish time (Spearman ρ correlation coefficient between the start time and the time remaining to finish was calculated) had shown that at Sigulda luge track the correlation coefficient is lower than at some other world tracks. The calculated coefficient at Sigulda track was 0.48 in female group and 0.36 in male group (more than 300 start attempts in each group during seasons 2006/2007 till 2010/2011 were analysed). At Lillehammer track, for reference, the correlation coefficient in male group was as high as 0.74. During the season athletes compete at various world tracks, at which the correlation between the start and the finish time differs, therefore start technique improvement is one of the main training goals, especially during the off-track trainings.

Two time intervals were measured during the start ramp trainings – a full start time and an "upper" time, which was registered shortly after the start jerk and first paddling arm stroke. Depending on the position of the last pair of photocells (imitating tracks' start portions of different length), the "upper" time explained from 38 to 74% of full start time variance in male group. These findings are in agreement with previously published data showing that the initial start phases play a major role in the total start performance. [2, 4]

Computer Modelling of the Luge Start

Taking into account the importance of the initial start phases, the computer model is created for phases II and III. During these phases the athlete and sled form a closed kinematic chain – athlete's feet are pressed against the sled, and hands close the chain through the start handles. The modelled motion begins when the sled starts its backward movement (beginning of phase II) and lasts till the handles release instant (end of phase III). Sled's movement direction changes at transition from phase II to III. An absolute ("World") coordinate system of the computer model is directed as shown at Figure 6. Analysis of motion capture data of all participants of the study had shown that during phases II and III the sled (segment SL) moves both on horizontal start platform and the sloped portion of the ramp, therefore in the model segment SL has three DOF– translation along X and Z axes and rotation around Y axis.

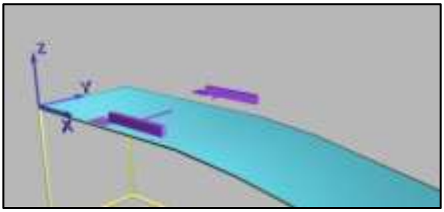


Figure 6. Location of World coordinate system origin

It was concluded from motion analysis of all the participants of the study that the athlete and the sled are not connected rigidly, and there exists relative translation of point Cox along the sled's longitudinal X_{SL} axis (Figure 7). No relative translation of point Cox was registered in other directions.

Planar Model of Torso and Sled Segments

The analysis had shown that kinematics of torso and SL segment can be modelled in plane, since among the participants of the study changes in y coordinate of these segments were not registered. To validate the planar model, in a first approximation it was assumed that at the sled and torso connection point (point Cox) the torso has one DOF – rotation around Y axis. Sled's DOF were limited to translations along X and Z axes; rotation around Y axis was restricted. Horizontal and vertical velocity of the sled coincided with velocity of point Cox. Kinematic chain of this sled and torso model (model A) is shown at Figure 8 (a). The endpoints of the torso segment are points C7 and Sacr; in planar model x and z coordinates of point Sacr coincide with coordinates of point Cox.

Three generalized coordinates (and their first two time derivatives) are necessary to simulate the motion with the computer model A – coordinates x and z of point Sacr, and torso angle to horizontal. Generalized coordinates can be obtained from motion capture results. Movement simulation with model A had revealed that this model does not imitate athlete's kinematics during the start precisely enough – the model-predicted coordinates of point C7 significantly differ from reference values (motion capture results). A two-segment torso model is required to simulate the motion more accurately (model B, Figure 8 (b)). Torso upper and lower parts have one relative DOF in point Th9 – rotation around Y axis.

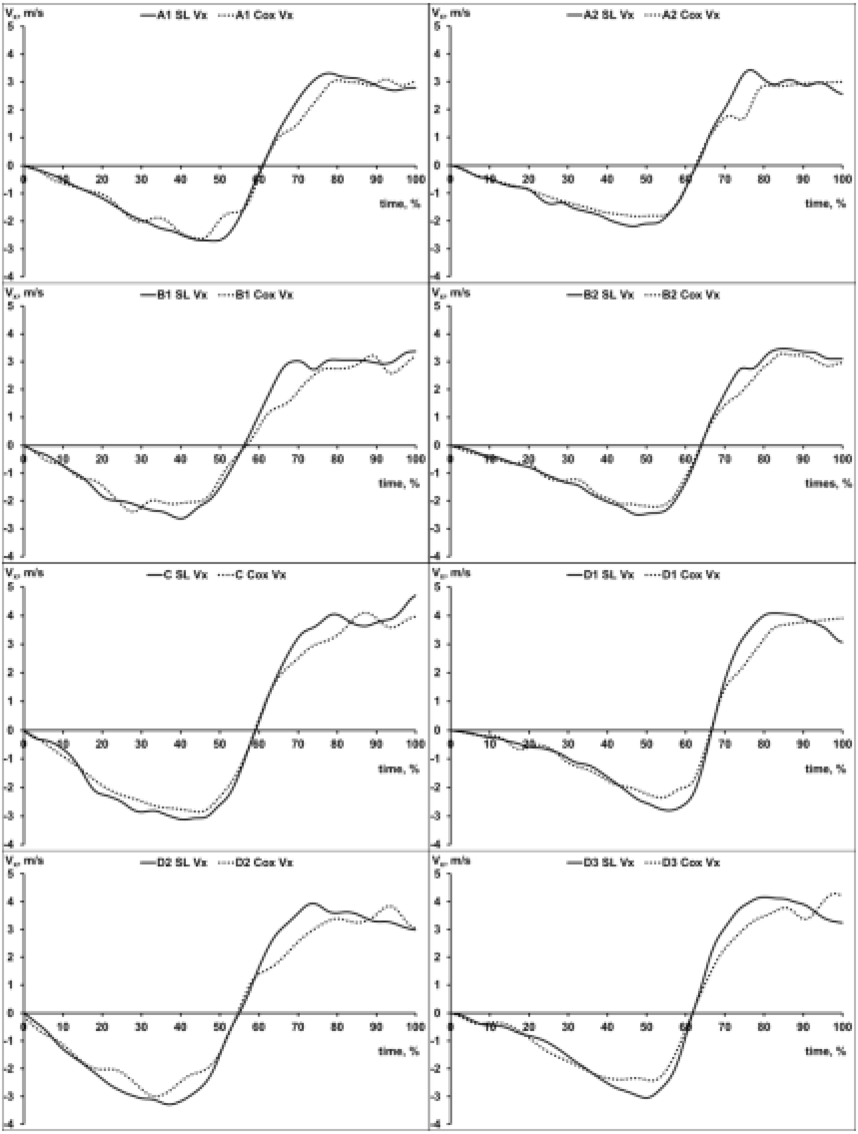


Figure 7. Horizontal velocity of the sled and hip during start phases II and III

Averaged velocity from 30 successful start attempts for each participant of the study; time is normalized to the total duration of phases II and III

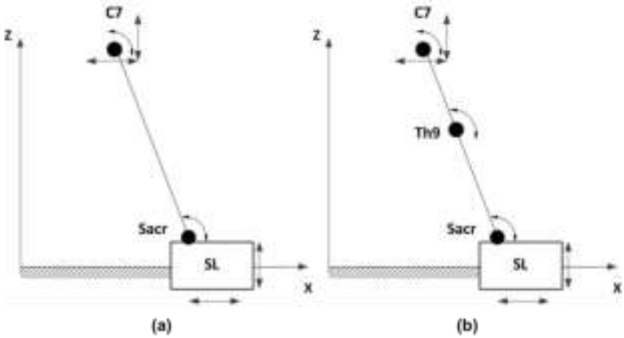


Figure 8. Kinetic chain of model A (a) and B (b)

Motion simulation with the model B requires one additional generalized coordinate – an angle between upper and lower torso parts. To avoid mapping of additional Th9 point in motion capture software, model B was modified into model B1 – at point C7 the upper part of torso was connected to a “virtual ground” with a planar 3DOF massless joint. This connection turns open kinematic chain into closed, and linear generalized coordinates of points C7 and Cox can be used for movement imitation instead of angular coordinates. This approach slightly complicates the computer model itself, but facilitates operations with generalized coordinates, since linear coordinates are much simpler to interpret for the given modelling environment than the angular coordinates are. In further modelling process the developed modelling approach was preferred – the kinematic chains were artificially closed without changing the total number of DOF of the system.

Movement simulation with model B1 produced coordinates of points C7 and Cox that coincided with the reference data, therefore in a simplest case, when sled’s rotation around Y axis is restricted, model B1 was considered appropriate for imitation of torso and sled kinematics.

3D Arm Model

Different 3D arm models were developed to determine the necessary number of segments and DOF. Movement simulation had shown that a two-segment arm model (consisting of upper arm and forearm segments) does not imitate arm’s kinematics accurately enough. Therefore a three-segment arm model was created. It includes upper arm (points Acr-Cub), forearm (points Cub-Man) and hand (points Man-Met) segments.

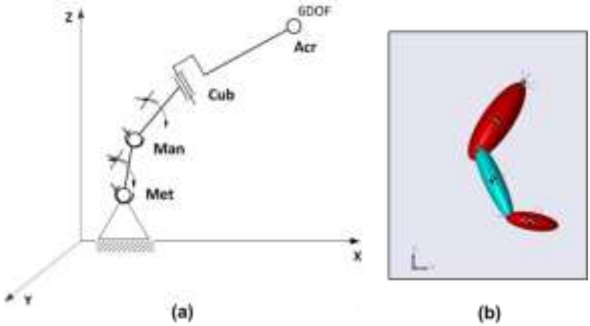


Figure 9. Arm model kinematic chain (a) and visualizing in computer modelling environment (b)

Upper arm and forearm segments have one relative DOF – forearm rotation around upper arm local Y_U axis. Hand segment at point Met can rotate around "World" Y axis and around hand local X_H axis.

Two hand-forearm models were developed to determine an appropriate number of DOF at wrist joint. Movement simulations had shown that one DOF at the wrist joint is not satisfactory, and at least two DOF are required – hand segment rotation around forearm local X_F and Y_F axes (Figure 9).

One-sided Upper Body Model

A simplified upper body model (model D1) is a combination of two previously developed models – the two-segment torso model and the three-segment arm model (Figure 10). It was found from motion capture data of all participants of the study that there are significant variations in shoulder point Acr y coordinate during the start phases II and III. Therefore the joint between the arm and the torso models has to imitate a kinematic shoulder segment. A spherical-spherical "massless connector" (consisting of two spherical joints separated spatially by a vector of constant length) from SimMechanics joints library was considered to be the most appropriate connection type in this case. To simulate the movement with model D1 two linear coordinates x_{Cox} and z_{Cox}, and six angular coordinates, obtained from arm and torso models, were used. Motion simulation was visually consistent with real athlete's movements and had produced coordinates of body landmarks that were very close to reference data

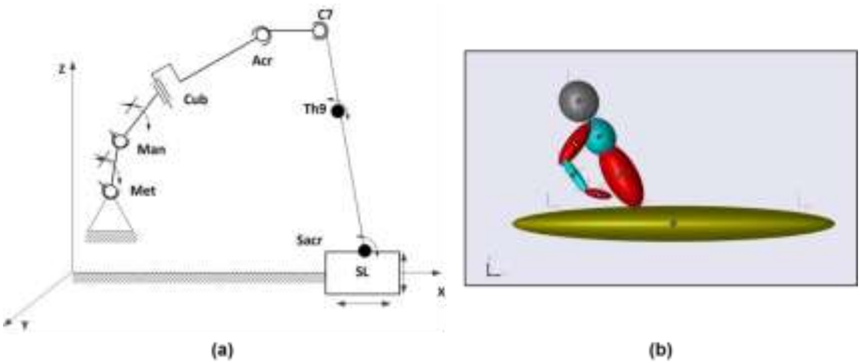


Figure 10. Upper body model kinematic chain (a) and visualizing in computer modelling environment (b)

Full Body Model

Before construction of the both-sided full body model the thigh (Cox-Con) and shank (Con-Mal) leg segments were added to the previous one-sided model D1. Also previously restricted DOF were included into the model – translation of torso along segment SL X_{SL} axis and SL segment rotation around Y axis. The thigh is connected at point Cox with spherical joint. The knee joint allows shank rotation around the thigh local Y_T axis. The shank is connected to the sled at point Mal with a spherical joint, which restricts all relative translations of the shank in this point. (Figure 11).

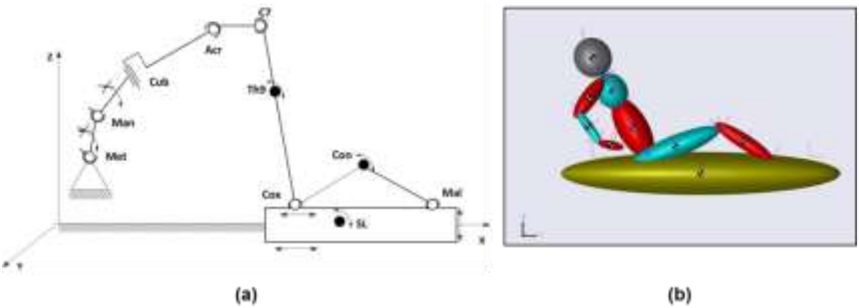


Figure 11. Full body model E1 kinematic chain (a) and visualizing in computer modelling environment (b)

Eleven generalized coordinates were used to simulate the motion with one-sided full body model (model E1) – eight coordinates were already used with model D1; the additional coordinates were: point SLb x coordinate, point Con y coordinate and point Mal z coordinate. Points Con and Man were connected to "virtual ground", as previously described in chapter "*Planar Model of Torso and Sled Segments*". The results of computer simulation had shown that model E1 accurately predicts the coordinates of athlete's body landmarks. To obtain the two-sided full body model in phases II and III of the start the symmetrical arm and leg segments were added to the other side of the model E1.

Estimation of Forces

Reaction forces and torques can be measured in the joints by adding joint sensors to the full-body model blocks. Segments' mass and inertia parameters input in the model are used for calculation of forces. Reaction forces at the start handles are of primary interest for quantitative evaluation of the start performance. Figure 12 shows a graph of the reaction forces obtained from the computer model at handle and hand connection joint. It is not currently possible to directly measure the forces at the start handles at Sigulda start ramp or track; therefore no reference data are available for the model predicted values. Nevertheless, the obtained force values can be used for the comparative analysis of the start attempts, and that considerably expands the possibilities of the start biomechanical analysis.

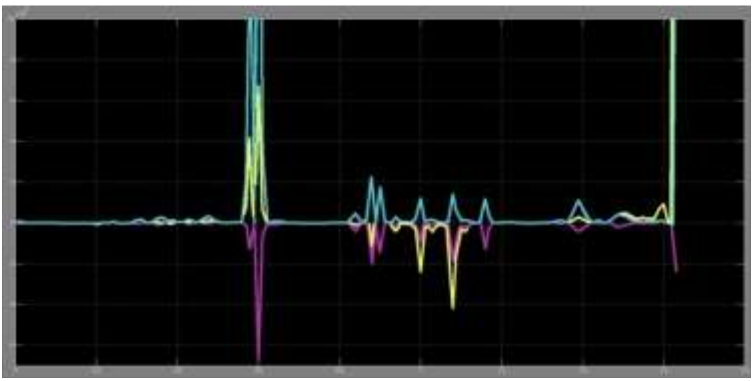


Figure 12. Reaction forces at handle-hand joint

yellow – force X axis component, purple – Y axis component, blue – Z axis component. In the graph: vertical axis–force, N, horizontal axis–time, s.

Visualization model of the start performance

The visualisation model was developed using Biped tool from 3ds Max software Character Studio module. The model includes the following elements: head, one-segment neck, two-segment torso, one-segment pelvis, thighs, shanks, feet, shoulders, upper arms, forearms and hands (Figure 13). Endpoints of the segments of the visualization model coincide with the “joints” of the kinematically-driven model.

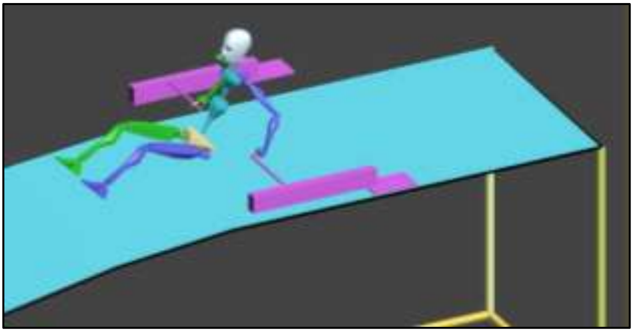


Figure 13. Visualization model of the start

The default body segments DOF of the Biped tool were used. The default DOF are close to the real human movement restrictions and prevent disconnection of the joints. In addition torso, neck and head movements were restricted to XZ plane. The feet were added purely of aesthetic considerations and rigidly connected to the shanks; kinematics of the feet was not assessed. The head was connected rigidly to the neck; the conjoint kinematics of these segments was governed by coordinates of points C7 and Vert.

Segment length of an individual model is obtained through anthropometric measurements of each athlete. As in kinematically-driven model, movement simulation with visualization model is performed using time-dependencies of the landmarks’ coordinates. These coordinates can be either imported from motion capture software, or from the kinematically-driven model. The visualization model is placed in the previously constructed model of the start ramp and is “moving” in the coordinate system of the latter. The accuracy of visualization can be confirmed through overlaying the visualization model view with a video record (Figure 14).

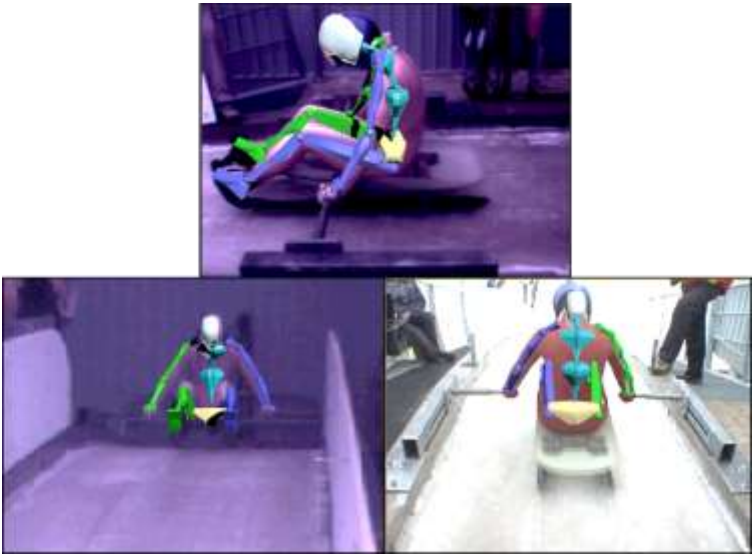


Figure 14. Three views of the visualization model and video record overlay

3ds Max software allows reconstruction of the coordinates of the model space (the start ramp in our case), which broadens applicability of the constructed visualization model. This model can be used to assess coordinates of the body landmarks of the athletes, as an alternative to the motion capture software. After overlaying the model and video record views in each frame in 3ds Max software, it is possible to obtain the coordinates of the model joints. Reconstruction of the coordinates from the linked-segment model is more accurate than by using single-point mapping technique (as in Simi Motion software), since the constant segment length is ensured.

The main applications of the visualization model are:

- visualization of the start from the most appropriate view, and convenient comparison of two or more start attempts (by overlaying the models or placing them side by side);
- visualization of a theoretically predicted movement with calculated kinematics, which had not been performed in reality;
- reconstruction of coordinates from synchronized video records with increased accuracy.

CONCLUSIONS

1. The developed kinematically-driven computer model of luging start allows realistic movement simulation during phases II and III of the start, sensing of reaction forces in joints and prediction of kinematic and kinematic variables of a theoretically optimized motion.
2. At least two segments are required to model the torso in luging start.
3. Three-segment arm model is required for an accurate computer modelling of the start in luging.
4. A minimum required number of wrist joint model DOF is two – rotation around anteroposterior and mediolateral axes.
5. During the initial start phases in luging an athlete moves relatively to the longitudinal axis of the sled, therefore the velocities of athlete's and sled's centres of masses are different.
6. The developed visualization model of the start allows visualization of the start movement in an arbitrary plane, an effective comparison of two or more start attempts of one or several athletes, visualization of a theoretically modelled motion, as well as refinement of the coordinates' reconstruction procedure.
7. Correlation between luge start and finish times varies at different world tracks.
8. The developed cameras' calibration procedure is applicable for reconstruction of spatial coordinates of body landmarks and other points from video records, captured at training and competitive environment of the athletes; the developed procedure provides accurate assessment of coordinates' values and comparing to the standard procedure considerably increases efficiency of the motion capture process.
9. The developed computer model of Sigulda start ramp is applicable for reconstruction of coordinates in lugers' start and is easily adjustable for bobsleigh and skeleton start analysis.

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