Are there characteristic movement variations in the take-off technique and do they affect performance related kinetic variables?

Ski jumping – a principal component analysis of technique training

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Abstract

Introduction. Part of technique training in ski jumping consists of land-based simulation jumps: athletes vary their sitting posture following instructions, such as "*high*", "*low*", "*offensive*", or "*defensive*", and evaluate the subsequent take-off motions with their coaches. This study addresses three research questions: (1) do different athletes interpret the different instructions in similar ways? (2) What characteristic variations are seen in the take-off kinematics? (3) Do changes in the sitting position and push-off kinematics affect kinetic variables?
Methods. Fourteen ski jumpers completed 21 imitation jumps under 6 different instructions: *perfect, high, low, offensive, defensive,* and *free*. The take-off movements were recorded with Oqus motion tracking system using 22 reflective markers distributed on the right extremities, pelvis, spine, and head. Two Kistler force plates recorded ground reaction forces (GRF). A principal component analysis (PCA) was performed on a combination of marker trajectories and kinetic variables. We assessed how changes in movement patterns (principal movements, PM_k) correlated with changes in the kinetic variables. The PCA was conducted on the normalised data from all subjects and thus allowed for direct comparisons of movement patterns between subjects.
Results. Despite individual differences, the instructions were interpreted largely similarly by the jumpers. $PM_{1\text{-}2}$ characterised movements due to the sagittal constraint of the take-off, reflected in anterioposterior and vertical whole-body variance throughout the take-off. $PM_{3\text{-}6}$ represented compensation movements in sitting position and push-off due to exaggerations in $PM_{1\text{-}2}$ sitting position. $PM_{7\text{-}10}$ characterised perturbations at the start of push-off. The kinetic variables showed distinct patterns representing the different movement variations.
Conclusion. Results indicated that jumpers interpreted the different instructions similarly. In addition, three distinct groups of movement characteristics were observed in the sitting position, during push-off, or both. Furthermore, movement characteristics and kinetic forces were related, although causality cannot be inferred from the present study. Visualisation of the PM_k can help coaches and athletes better understand the often ambiguous descriptions of movement patterns and variations, which again could help in take-off technique training.

Preface

The biggest gratitude goes to my family for bearing with the excessive energy and all the craziness I gladly offered up as a child. Allowing, even encouraging, this gave the inspiration to explore and ask questions.

My supervisors are thankfully the best of both worlds.
Peter A. Federolf, with an unknown Euclidean distance of knowledge about everything I don’t know anything about, and ability to be patient enough to teach me some of it. Thank you for getting into this project we knew nothing about.
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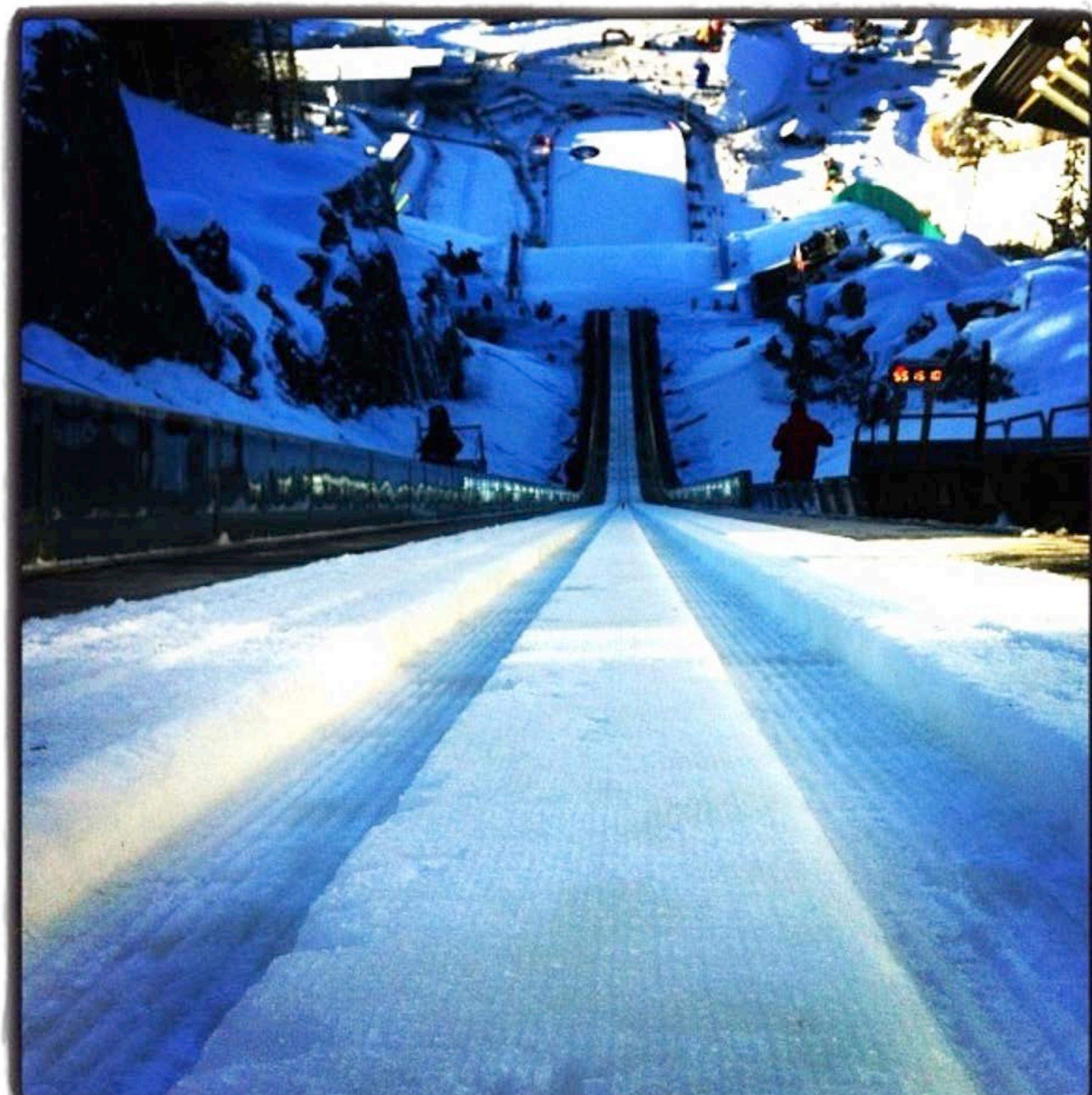
To Eirik, the right and left hand of my data collection, Lars Peder, the idea bouncer and listener, and Mirko, the MatLab prodigy. The first principal components of getting through a year of hard labour!



Contents

1 Introduction

Ski jumping is a technically complex sport where the short and critical transition from having the feet on the ground to being airborne, done through the take-off at the end of the in-run, requires great control over physiological, technical, and mental aspects. This makes optimal performance highly vulnerable to even the smallest variations, and how technique training is executed is therefore paramount. Coaches and athletes aim for better understanding of the effects of different training tasks and regimes they implement, including the movement variations that should be expected from different training instructions. A thorough understanding of these aspects will help communication and evaluations between athletes and coaches, and assist in finding better exercises to meet the desired criteria's for overall performance success.

1.1 Take-off technique training

Technique training in sports consists of both highly specific exercises, and exercises that challenge, in differing amounts, the variations around an optimal execution. The major challenge in ski jumping training is the difficulty of getting actual hill training, which is the most specific form of training. Weather conditions, equipment and time of execution are all factors that lead to, in periods, a land-based take-off technique training versus actual hill training ratio of up to 20:1[1]. This means that for ski jumping the land-based training is essential for evaluating factors affecting the take-off movements and performance on hills. Land-based training ranges from physical conditioning (e.g. power training, mobility), body awareness, and different jumping motions, to more specific technique exercises called simulation jumps. Within simulation jumps the most specific training is called imitation, and is executed from a sitting position mimicking the position held during the in-run, through a push-off jump and ending with a coach catching the jumper mid-air. Simulation jumps can be done from a static position or the jumpers can use ramps with wheels, rollerblades, etc. to give a sense of forward motion. However, the actual conditions and the feeling of a real in-run cannot be recreated outside of a hill. During simulation training, coaches will challenge the jumpers to perform the take-off motions based on different instructions. These instructions may differ from coach to coach both in subjective understanding and expectations, but also within different schools and methods of what is perceived as an optimal take-off technique.

1.1.1 Assessing take-off technique training

The in-run and take-off are largely two-dimensional (2D) movements best understood in the sagittal plane[2]. Mediolateral movements would create unwanted friction between the skis and tracks during the in-run, and dangerous rotational movements during the transition to the flight phase; hence they should be avoided. When ski jumpers train the take-off with their technical coaches, they almost exclusively vary and assess the effects of the anterioposterior and vertical movement variations[1]. There is no common consent on how these variations of movements are interpreted by jumpers, but based on feedback from coaches the anterior option is expected to be a whole body movement taking the jumper more to the toes of the feet which is called offensive, and the posterior taking the jumper towards the heels, called defensive. Larger angles in the lower limb joints and an elevated spine are considered a high position, and the opposite a low position. These different configurations are some of the conditions that coaches can instruct a jumper to play around with, and are used to evaluate a jumper's movement execution. However, complicating the picture is the fact that the jumpers' individual interpretations of these instructions may vary, especially if the conditions are to be executed only during the sitting position, the push-off, or both. After all, the take-off consists of two different motions – the sitting position, a rather static posture, and the push-off, a dynamic movement where the legs are rapidly extended, while trying to maintain the horizontal, aerodynamically advantageous upper body position established in the sitting position.

1.2 Ski jumping research

Studying ski jumping is difficult to execute on hills, especially the equipment needed for measurements is challenging, not least for the jumpers safety. Nevertheless researchers have been able to explain the different stages of a ski jump[3–5], and take-off is consistently described in the literature as one of the, if not the, most critical stage[3,4]. Great effort is used to understand both the kinetic demands during the in-run and take-off, and the kinematics explaining the actions of the take-off movements[6–10], with the goal in mind to pinpoint and understand what is needed for optimal performance; in other words the end goal of the technique training, which is only an indirect assessment of how different technique training affects performance[4].

Before going further, two issues are worth mentioning regarding ski jumping research. Firstly, the research field is small, with only a few research groups focusing on specific aspects. These groups are often closely linked to the national ski associations, with the main countries being Norway, Austria, Germany, Finland, Japan, Switzerland and some East-European countries. Therefore, part of the data from research on ski jumping may never be published[6] because of the competition between the few main countries mentioned, especially when the national associations are a driving force[4], leaving gaps in the available knowledge of ski jumping[7]. Secondly, it is difficult to directly compare studies, especially the ones done on hills. Different, and changing, track and weather conditions, varying amount of subjects and trials, and different instrumentation could all lead to direct comparisons being sensitive to erroneous interpretations and conclusions[11].

1.2.1 Mechanical performance variables

Ski jumping is essentially a ballistic problem – the launch (in-run and take-off), flight, and behaviour of the projectile (jumper and skis) are strong determinates for the jump length and therefore the performance success. The jumper can directly affect both the speed gathered during the in-run by applying the most aerodynamically efficient sitting position[12], and how well the take-off movements is executed[13]. From ground reaction forces (GRF) measured, vertical impulse (VI) and moment are currently considered the two main mechanical performance variables (MPV) that indicate the success of the take-off action[4]. This is because they together create a cohesive picture for coaches and athletes of the kinematic and kinetic relationship between vertical force production (VertF) and forward rotation needed during take-off[10,14]. ***Vertical impulse*** is force integrated over time and is used as a MPV because it reflects how fast a jumper can reach a certain height. The shorter the time in which a maximum height can be reached, the faster the athlete can potentially get into the flying position and hence minimise the period with high air resistance. The best jumpers reach their peak force in approximately 0.3 seconds from the start of the push-off in the sitting position[15], and reach the greatest heights above the take-off table[16]. Dividing impulse by mass gives velocity, and as such VI also indicates at what velocity a given mass can be moved, a measure of the explosive quality of a jumpers power. Power is amount of mechanical energy divided by the time period needed to create this energy and a jumper can therefore directly affect the VI through power training. It is, however, critical to emphasise that the movements used to create the VI must not compromise "optimal movements" through the take-off[13]. However, what constitutes an "optimal movement" is difficult to define; maximising VI and rotating the jumper forward into the flying position while minimising air drag are important aspects. The overall physical condition of the jumper will determine how well the jumper can create the VI needed, and still execute optimal movements for reaching the flying position. ***Moment*** is amount of force applied to a body over a distance (i.e. over a lever arm). During a jump, a moment is created when there is a distance between the GRF centre of pressure (COP) and the vertical projection of the centre of mass (COM) onto the force plate (often called "centre of gravity", COG[17]). The COP is the application point of the ground reaction force vector. This vector is the sum of all forces, x y z, acting between the jumper and the surface. The COM is the point where the weighted relative position of the body's mass distribution sums to zero. It is a virtual point which might not necessarily be located on the body, as may be the case during ski jumping[7]. In dynamic movements such as the take-off, the COM displacement will be large. The amount of forward rotation must be perfect; too little rotation and the jumper stalls, breaking the speed gathered, while too much could take them into a nosedive. COM can be calculated from both kinematic and kinetic data[3,7], but unfortunately calculating COM is not something that is easily at hand outside the research area. This means only the best and most experienced coaches can estimate the forward rotation needed based on COP based moment calculations, which is given by the GRF data from force plates. Therefore relying solely on the change in COP must be treated as a rough approximation of the COM, and hence the moment.

1.2.2 Take-off technique research

The sitting position during take-off is strongly affected by having just come out of the curved section of the in-run, and the centrifugal and compressional forces acting on the jumper in the curve mean some form of movement alterations must occur to prevent the jumper from loosing balance[7]. Entering the take-off table the jumper wants to be in balance, but what balance means depends on different schools of thought. Some jumpers will consciously use the compression forces in the curve as a natural countermovement preparing for take-off; others maintain a more rigid posture focusing on keeping the COP and COG in an optimal relation. Others again will hang on to the metal rod on the binding, trusting this to stop unwanted perturbations through the curve. No matter what solution is preferred, coming into the take-off table there must be a VertF[4] which must be created through a rapid leg extension to create the VI. This push-off motion is associated with a regular vertical squat jump, a part from two main aspects. Firstly, the stiffness of the ski jumping boots prevents normal plantar flexion, meaning that the same amount of force cannot be produced compared to jumping barefoot, or with normal training shoes[18,19]. The restricted ankle joint movement leaves more of the force production to the thighs and knee joints[19], along with the gluteus muscles and the hip joint[4,11]. But the hip joint is also controlling the upper body angle throughout the push-off[20], which takes us to the second main difference from a normal squat jump. In a regular squat jump the upper body leads the push-off motions[21], followed by the leg extension. This has the benefit of freeing the legs of the load of the upper body. However, this cannot be done in a ski jump push-off since an upright upper body increases air resistance and would break the speed gathered through the in-run. Equally, this raising of the upper body would mean that the forward rotation needed to reach the flying phase would be too large to overcome or take too long to execute[22]. The hip joint angle is important for the raising of the upper body, and different amount of joint angles have been found, but as long as the time used in a rising motion is short enough, this does not necessarily affect jump length negatively because the flying position is reached[23,24]. The timing of all these different movements is another critical aspect, and a general assessment of the literature suggests that the knee joint (thighs) should initiate the push-off phase, followed by the hip joint and the forward rotation movement[4,20]. The shank (ankle joint) is kept stable as long as possible and is the last main segment moving in the movement chain[11,20]. This movement model explains how the best jumpers are able to create the most vertical force taking them higher above the take-off table, and reaching the flying position faster, but it does not take into account the high variability seen in take-off techniques[23–25], even between the best jumpers[12]. Assessing what is wrong or right should not be judged without understanding the whole-body movement variations[20], maybe especially the variation in amount of hip opening and upper body movement. It is even suggested that looking at different training exercises will help building a better picture of the movements during take-off[7].

1.3 Purpose of the current study

Based on the knowledge of the different kinetic demands during the in-run and take-off, the biomechanics of the jumper are usually quantified and assessed using three main body segments: foot and shank (justified due to the limited plantar flexion), thighs and upper body and head. The leg extension and the internal timing and the movement coordination of these segments are well described, also in terms of performance[3,4,11,20]. However, describing the upper body as one single structure with no internal movement variation, and a lack of sufficient explanation of the pelvises involvement with both the upper and lower body means vital information about the kinematics is left out. The spine is involved with three major body segments, pelvis, thorax, and head. Furthermore the spine itself consists of 33-34 vertebras, all its own joint, that is grouped into three major freestanding sections, lumbar, thoracic and cervical (the sacral section lies within the pelvis). This means there are multiple movement variations possible throughout the upper body that possibly can affect, and will be affected by, the transition from the deep sitting position through the explosive push-off. Chardonnens (2013) specifically calls for more research connecting the well-established lower body motions with the whole-body movement, which in terms might help build a more cohesive kinematic understanding within a solid kinetic foundation.

1.3.1 Research question

From Bernstein's problem and the hypothesis on the degrees of freedom, we know that individual jumpers solve movements differently, and that individual jumpers never perform the same movements twice[26]. This inherent variation along with the lack of knowledge on whether and how the sitting position and, or push-off motions during the in-run affects the overall take-off movements based on different training instructions and conditions warrants a closer look; furthermore, how these movements affect different kinetic variables should be included for a more detailed picture of take-off performance. To better understand kinematic actions during imitation jumps, we will implement a principal component analysis (PCA). PCA has been shown to help in evaluating the underlying aspects of whole body movements[27–29], and by including GRF into the analysis[30] we aim to answer three research questions: (1) do different athletes interpret the different training instructions in the same way? (2) What characteristic variations are seen in the sitting position and push-off kinematics? (3) Do changes in sitting position and push-off kinematics affect kinetic variables? It is hypothesised that athletes interpret the different instructions similarly, and that different conditions for sitting posture and push-off kinematics are related to changes in kinetic variables

2 Methods

2.1 Participants

Fourteen male ski jumpers (22 ± 5.3 years; 177.1 ± 6.5 cm height; 61.4 ± 5.7 kg weight; 26.3 ± 1.2 cm foot length) from Trønderhopp ski jumping club participated in the study, and all gave their written consent for participation prior to data collection. Six jumpers were juniors with some having international competition experience, the remaining eight were elite level where everyone had international experience. The data was collected over five days: juniors during two days in September, elite jumpers during three days in November. Coaches from Trønderhopp and a national team coach were present to catch the jumpers in mid-air.

2.2 Equipment

2.2.1 Reflective markers

In total 22 markers were used on the following anatomical landmarks. Right extremities: interphalangeal joint of the big and little toe, intermedial cuneiform, lateral malleous, calcaneus, tibial shaft, lateral femoral condyle, hamstring, trochantar major, dorsal wrist, lateral epicondyl, and acromion. Pelvis: left and right SIPS. Spine: L3, T10, T5, C7, one on the manubrium, and a headband with a front, side and back marker (see Figure 1).

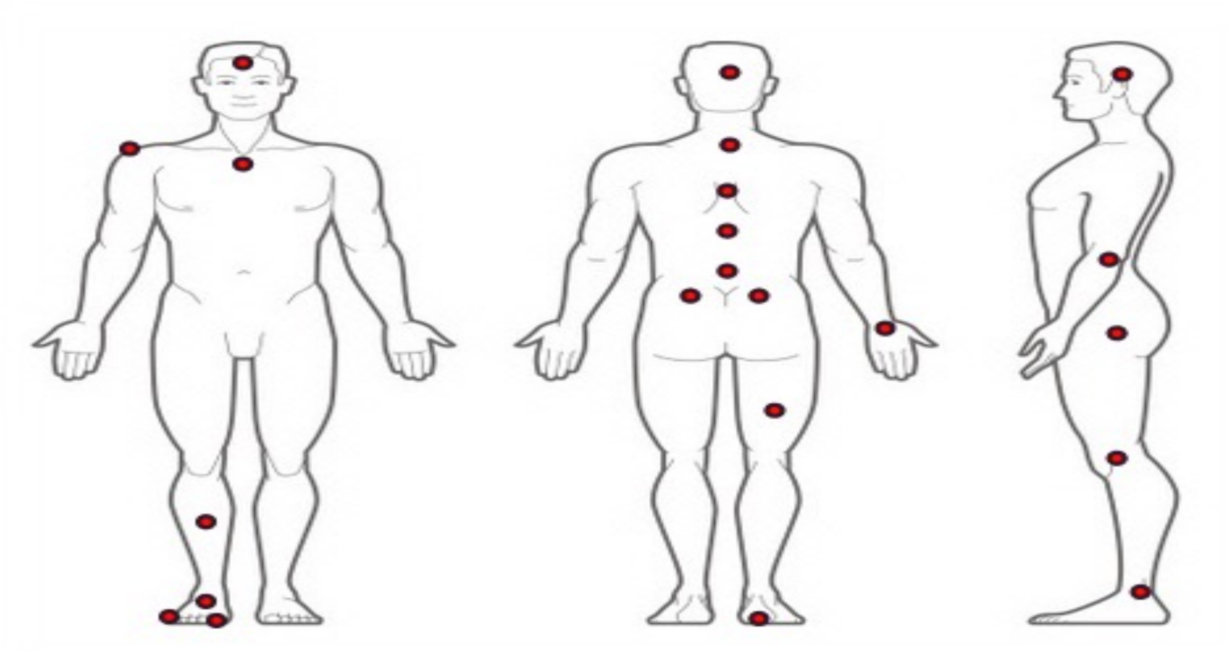


Figure 1. Marker set up

2.2.2 Instrumentation

The kinematic data was collected in three dimensions (3D) using six cameras from the Qualisys motion analysis system (Oqus 400) at a sample rate of 250 Hz. Two Kistler 9286BA force plates (600x400x35 mm) collected kinetic data (GRF) at a sample rate of 500Hz; one placed in front of the other with the long sides facing each other, and a metal rod crossing the back plate at 13 cm from the gap between the two plates. The rod was the limit for how far back the jumpers could place their heels including the marker placed on the calcaneus. Qualisys Track Manager software (QTM) synchronised data from the force plates and the motion capture system.

An analogue Sony DCR-VX200E PAL with standard 25 frames (interlaced 50 fields) was used for high-speed video recording of each jump. This was not synchronised in QTM and was collected separately on a cassette (MiniDV) using Sony Digital Video Cassette Recorder GV-D1000E PAL. These recordings were primarily for Trønderhopp and Olympiatoppen Midt-Norge (OLTMN).

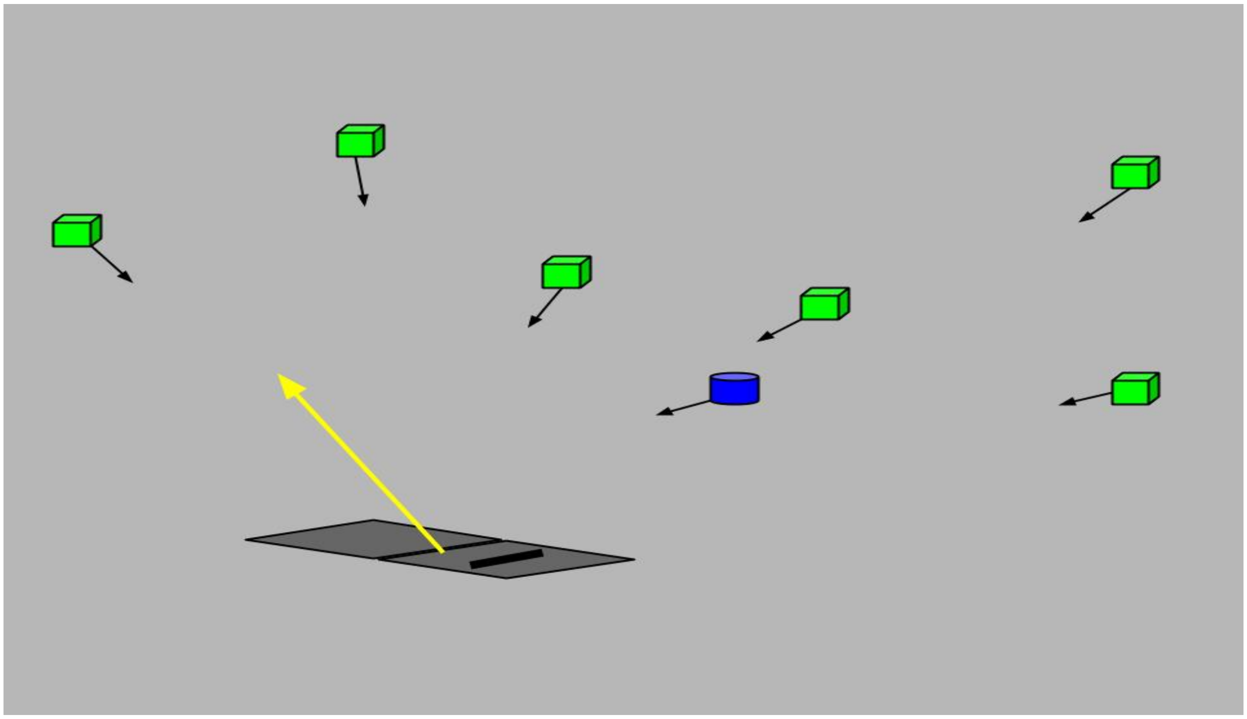


Figure 2. Instrumentation set up with jump direction (yellow arrow). Grey square = fore plate, black line = metal rod, green square = Oqus camera, blue cylinder = analogue camera

2.3 Procedures

2.3.1 Conditions

Six different conditions were used. 'Perfect' was briefly explained as being the execution of the take-off closest resembling how they would perform on a hill to achieve the greatest jump length. The 'offensive', 'defensive', 'high' and 'low' conditions were based on the coaches' descriptions of the anterioposterior and vertical variations used in technique training. They were randomised in blocks, as we did not want the relationship between offensive and defensive, and between high and low to be broken. This randomisation yielded eight different orders. A 'free' condition was added to give the jumpers an opportunity to play around with their technique, e.g. exaggerate, minimise, or do something totally different.

2.3.2 Protocol

Every jumper did three jumps in seven sets, for a total of 21 imitation jumps. Perfect was always the first and sixth set, and free the last, for example perfect, offensive, defensive, high, low, perfect, free. In total 294 trials (14 jumpers x 21 trials) were measured.

Standing on the force plates each jumper was first told which condition to perform, and then given a signal to get into the sitting position, and a reminder of the condition was given. The position was held for 4-5 seconds before being given a clear verbal instruction (‘‘jump’’) to execute the push-off, taking them from the sitting position into an elevated position supported by the coaches (Figure 3). On average each trial lasted between 30 to 45 seconds before the next trial could be started. The jumpers were barefoot and only wore tight cycling shorts. Reflective fabric on clothing on jumpers and coaches was covered with masking tape, to avoid interfering with recordings.

Figure 3. Still images from an imitation jump

2.3.3 Self-assessment

It was vital that the execution of each trial was based on each individual jumpers subjective interpretation of the conditions, e.g. what offensive meant for their own sitting position, push-off, or both. The test leaders and the coaches did not comment on the jumpers’ execution, nor were questions, comments or interpretations of the conditions from the jumpers during the data collection elaborated on. Immediately after every trial the jumpers subjectively assessed their own execution of the condition according to the instructions, not whether the trial would have taken them far down the hill, on a linear analogue scale measuring 10 cm (see Figure 4). After the data collection, coaches and jumpers were free to discuss what had been observed from their point of view.

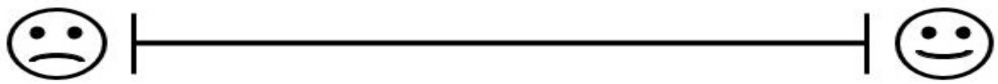


Figure 4. The linear analogue scale on which jumpers scored how well they executed each condition

2.3.4 Test responsibilities

The test leader made sure all necessary information was given prior, during and after measurements, and collected the subjective self-assessment data. A test assistant had responsibility for giving the cues for executing the take-off movements, checking that all the data was collected, and saving the data after each trial and at the end of each test day. Preparation of each participant was done in collaboration. As the test assistant was a qualified physiotherapist, the anatomical landmarks for the markers were properly located.

2.3.5 Approvals

A regional ethical committee (REK) approval was granted, and the study was registered with the Ombudsman for Privacy in Research, Norwegian Social Science Data Services, AS.

2.4 Data analysis

All measured data was analysed using MatLab (R2014b, The MathWorks Inc., Natick, MA, USA).

In earlier PCA studies, ‘postural vectors’ have been used to decompose the static and cyclic movements in postural control and gait[27,28,31]. However, in non-cyclic and dynamic movements such as the take-off, assessing the waveforms are better suited[30] All marker trajectories recorded in one trial were interpreted as a vector in a high-dimensional vector space. The 21 trials from each subject formed an individual “solution space” for the take-off movement. The data analysis was comprised of two main procedures. First, three steps of data preparation were done with the goal of creating one comprehensive matrix consisting of the kinematic and kinetic data of all trials for all subjects. Secondly this matrix underwent a PCA to decompose the complex whole-body take-off movement, and correlate these components with the kinetic data.

2.4.1 Data preparation - PCA

(1) Selection of relevant data

For each trial the moment of take-off was determined as the first instance where the vertical GRF was smaller than 10N. Then a time period from 1000ms before take-off to 100ms after (276 marker frames, 551 vertical force frames) was selected. In the COP data the period from 1000ms before take-off (500 frames) was used.

(2) Gap-filling missing marker data

Gaps in the marker data set were reconstructed using the information from all available marker trajectories to correlate the appropriate location of the missing markers. Each result of the gap-filling was checked separately for each trial. Using all available data was especially important since the whole movement analysed is both a static and dynamic movement joined together. The gap-filling algorithm used is described in Federolf et al., 2013.

(3) Normalisation

a) Subtracting the mean trial vector of each subject from every subjects trial

   This process places all 14 waveforms ("solution spaces") in the same origin. The mean trial vector was given by calculating the mean of every waveform over all trials of an individual jumper.

b) Divide each trial vector with their mean Euclidean norm

This step is necessary to minimise differences in the expansion of the waveforms due to anthropometric differences. After this step each subject contributes the same amount of variance in the data set, while the relative amplitude of the markers is preserved. This is an advantage compared to common normalisations[28].
Calculating the norm of each jumper's trial vector, and then the mean of this norm over the entire trial gave the mean Euclidean norm.

c) Multiplying the waveforms of each marker with a specific weight factor

To ensure every marker represents the fraction of body weight it belongs to, a weight vector was constructed, containing a weight factor specified for each marker. By dividing the weight of the segment where the marker was attached, with number of markers located on this segment, the specific weight factor for each marker was calculated. Where the marker is located on a joint, it has been treated as a combination of the two segments. Hence, the weight of both segments was considered.
By multiplying all weight factors for markers placed only on the right extremities with 2, we ensured equal mass distribution, which is important for the kinetic analysis.
The specific weight for each segment was collected from US Air Force and National Aeronautics Space Administration calculations[32].

d) Dividing force with body weight

To implement the kinetic data in the final matrix the GRF was normalised to body weight. The kinetic variables implemented in the PCA were vertical GRF and COP.

2.4.2 Principal component analysis

The PCA was applied to the normalised matrix concatenated of 19267 x 294 vector components (([22 markers * 3D] * 276 time points for each waveform + [551 + 500 kinetic frames]) x 294 trials), resulting in three outputs; eigenvectors, eigenvalues and scores[27,31]. Eigenvectors (EV_i)

indicate the direction of the largest variance in the data set; eigenvalues (eV_i) indicate the amount of variation in % of any given EV_i, and hence the hierarchical ranking of the EV_i. Finally the scores (sc_i) identify the amplitude of the EV_i that each jumper deviates from the mean in each trial. In summary, a PCA decomposes complex multi-segment movements into one-dimensional linear movement components, and these components have been called ‘principal movements’ (PM_k)[29]. When visualised the different PM_k can be assessed much like coaches and athletes will in real time and through video recordings.

2.5 Summary of variables assessed in the current study

Variations in the execution of the jump were assessed using the variables obtained in the PCA:

- The eigenvectors, EV_i, characterised correlated deviations from the mean marker or force waveforms. The EV_i could be visualised using animated stick figures and VertF or COP graphs.
- The eigenvalues, eV_i, quantified how much of the total variance was represented by each EV_i.
- The scores, sc_i, allowed comparing differences between jump conditions or the assessment of the behaviour of individual jumpers. In the current study, for each subject mean sc_i were calculated over the three repetitions in each condition.

3 Results

We assessed the first 10 *PMs*, which together explained 95.1% of the variation in the take-off movements (see Table 1).

PM_k	1	2	3	4	5	6	7	8	9	10
eV_i	*44.4*	*23.3*	*13.9*	*4.4*	*2.9*	*2.7*	*1.5*	*0.8*	*0.6*	*0.6*

Table 1. Eigenvalues (eV_i) of the first 10 principal movements (PM_k) in % of total variance

3.1 Assessment of jump variations

The two figures below (Figures 5 and 6) show boxplots and plot graphs for PM_1 and PM_2. The boxplots show the sc_i distribution (y-axis) in each condition (x-axis). The line graphs show individual sc_i (y-axis) of each jumper (x-axis) in each condition (colour). The dots were connected with lines between jumpers within conditions to better visualise the link to the boxplot, but no relationship between the jumpers is suggested. PM_1 showed large deviations in the offensive and defensive condition (Figure 5), PM_2 in the high and low condition (Figure 6), while PM_3 showed smaller deviation in the high and low condition. $PM_{4\text{-}7}$ had narrower PC-score deviations around the mean, but some distinct outliers for individual jumpers, while $PM_{8\text{-}10}$ only showed minor variations. Two aspects represented in these figures are also important for an analysis of individual *PMs*. Firstly; the figures show how, in all *PMs*, the jumpers could have variation in movement characteristics in either positive or negative direction. Secondly, the figures indicate by which factor the stick-figure animations of the different *PMs* should be amplified for a realistic representation. See **Appendix (A.1)** for boxplots and plot graphs for all first 10 PM_k.

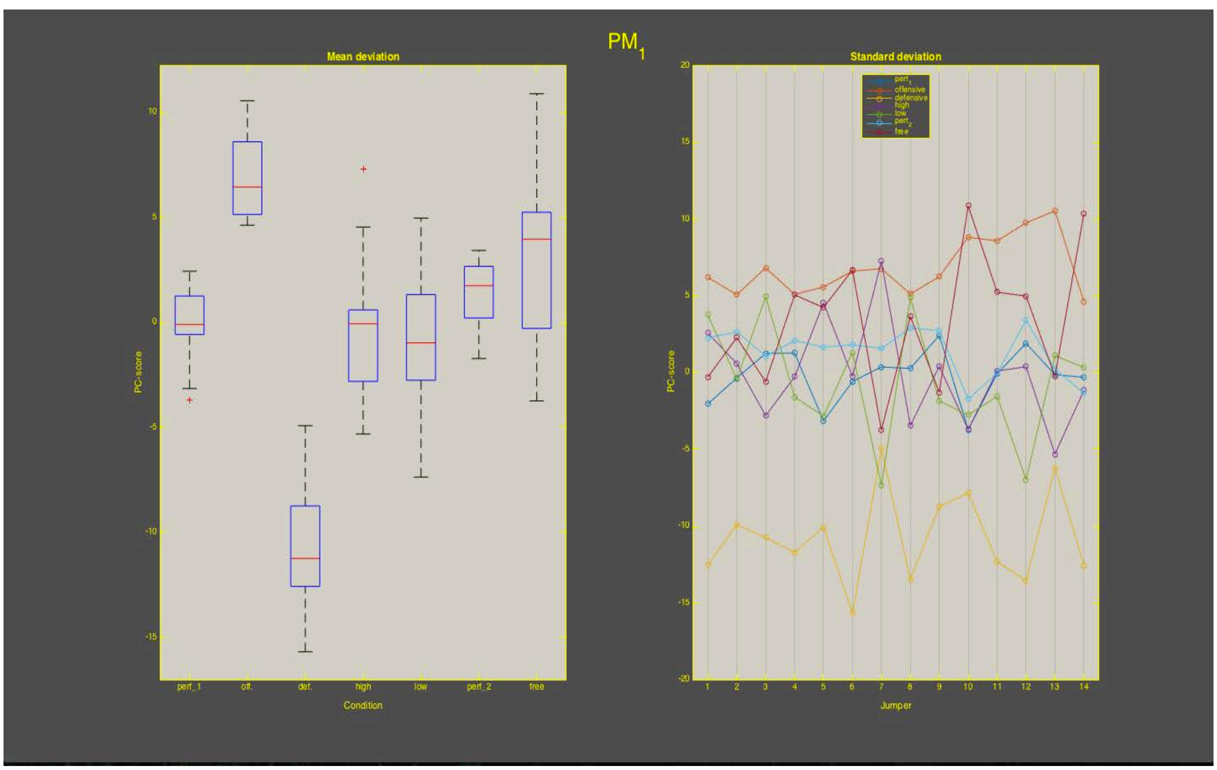


Figure 5 Distribution of sc_i for PM_1 over different conditions (left) and for individual subjects (right)

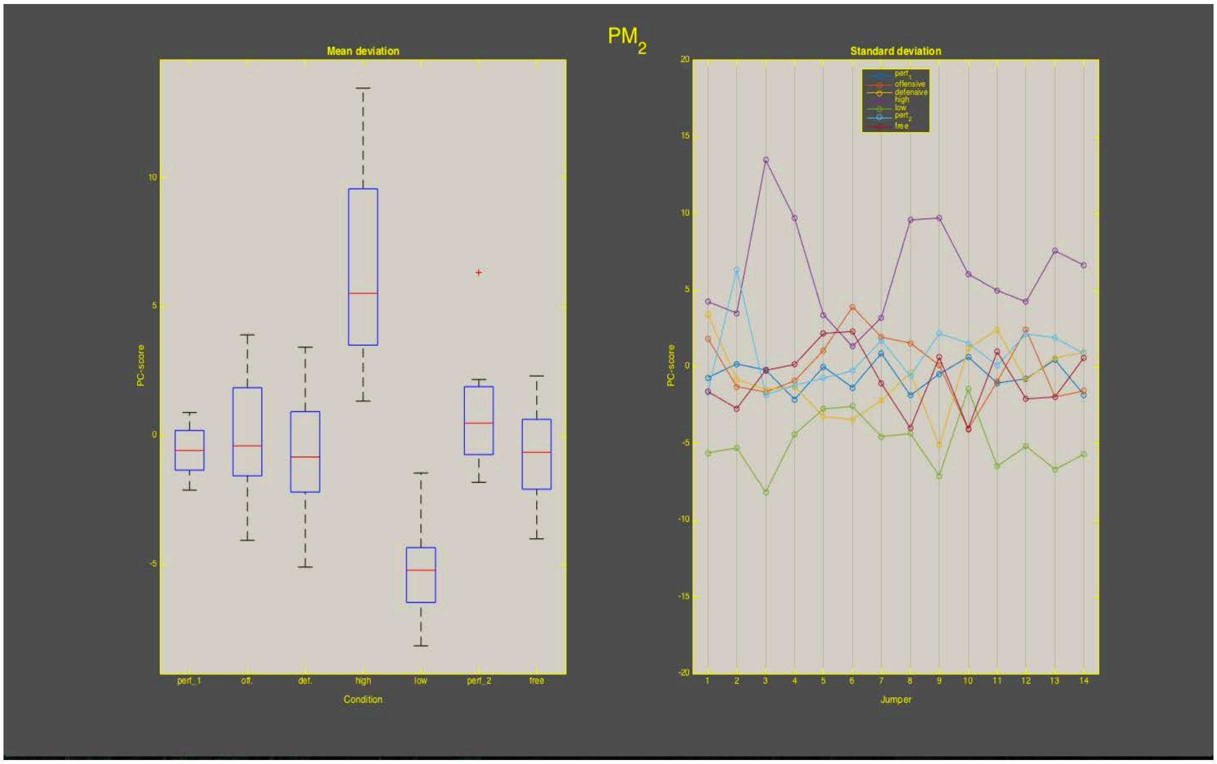


Figure 6. Distribution of sc_i for PM_2 over different conditions (left) and for individual subjects (right)

3.2 Movement characteristics, vertical force production and COP

In PM_1 a whole-body anterioposterior shift throughout the take-off was observed, reflected in a distinct difference in the COP location from the mean. The VertF showed a later push-off activation, with higher peak force for offensive (anteriorly shifted) jumps, and the opposite for defensive (posteriorly shifted) jumps (see Figures 7 and 8). The defensive jumps also showed larger score amplitude (Figure 5) than the offensive jumps, suggesting that the jumpers tended to a more offensive jump execution also in the other jumps with unrelated tasks.

PM_2 represented a whole-body vertical shift, throughout the take-off movement. The COP showed small differences from the mean, while the VertF curve for a high position resulted in later and lower initial VertF, but higher peak force. The opposite was observed in the low position. An upward shift of the body position had a larger score amplitude than the downward shift (Figure 6), suggesting that there was a general tendency in all jumps to assume a low posture. Together $PM_{1\text{-}2}$ explained 67.7% of the total variance seen in the take-off movement.

PM_{3}-$_{6}$ together explained 23.9% of the total variance, and characterised variations in both sitting position and push-off from the mean.

PM_3 represented a vertical shift of the pelvis: lifted (positive sc_i) or dropped (negative sc_i) during the initial sitting position. In the push-off movement, PM_3 lead to a whole-body end position that was lower (positive sc_i) or higher (negative sc_i). Hence, relatively small upward shifts of the pelvis in the sitting phase were correlated with a forward oriented, lower body position in the push-off phase. PM_3 showed minor differences in VertF from the mean, while the COP showed a small, but noticeable shift in the opposite anterioposterior direction during push-off. Both, the change in postural movement and the COP waveform suggest that a larger forward rotation is produced by the jump variation represented by positive PM_3 sc_i (see Figures 9 and 10).

No distinct movement differences were observed in PM_4, but when a larger amplitude factor (10, -10) was used, coaches suggested it could be a consequence of some jumpers having a longer back; the normalisation does not separate the different movement consequences of having different body sizes. PM_4 characterised small but observable differences in COP, and no distinct differences in VertF.

The PM_5 sitting position showed whole-body shifts in the anterioposterior direction, supported by the COP pattern, which was comparable to the PM_1 COP pattern, but with smaller amplitude. As with PM_3, the direction of the shift in initial sitting position represented by PM_5, was reversed during the push-off. In other words, an anteriorly shifted sitting position correlated with a posteriorly shifted body position after push-off. The VertF pattern resembled the pattern seen in PM_2, but the pattern shown in the positive PM_2 corresponded to negative shifts in PM_5, and vice versa.

PM_6 had a similar COP pattern as observed in PM_1 and PM_5, but unlike the shift in the whole-body sitting position in the anterioposterior direction in PM_5, the shift was now observed as a vertical curvature in the spine; as with PM_3 a distinct lift or drop of the pelvis was observed, but this is now correlated to a drop or lift of the chest and shoulder area. This initial position is also kept throughout the push-off, but with the pelvis catching up with the mean position. The VertF patterns were similar to the PM_5 pattern, but with smaller amplitude.

$PM_{7\text{-}10}$ was initially amplified by a factor of 10 or -10 to better visualise the *PMs* (as were all *PMs*) because of the low eV_i. They represented different limb, wave-like upper body movements and compensations at the start of push-off, but when using a more realistic amplification factor based on the sc_i (PM_7 PM_8 factor 2 and -2, PM_9 PM_{10} factor 1 and -1), these differences were hard to distinguish in the stick figures – apart from PM_7 which showed a vertical countermovement in the arms and upper body. The COP and VertF patterns in PM_8 exhibited large variations from the mean, as did the COP in PM_{10}, but again it was hard to explain what movement variations were related to these kinetic differences. Together $PM_{7\text{-}10}$ explained 1.9% of all the variation and apart from PM_7, none explained more than 1% of the variations. Figures of the first 10 PM_k are presented in **Appendix (A.2)**.

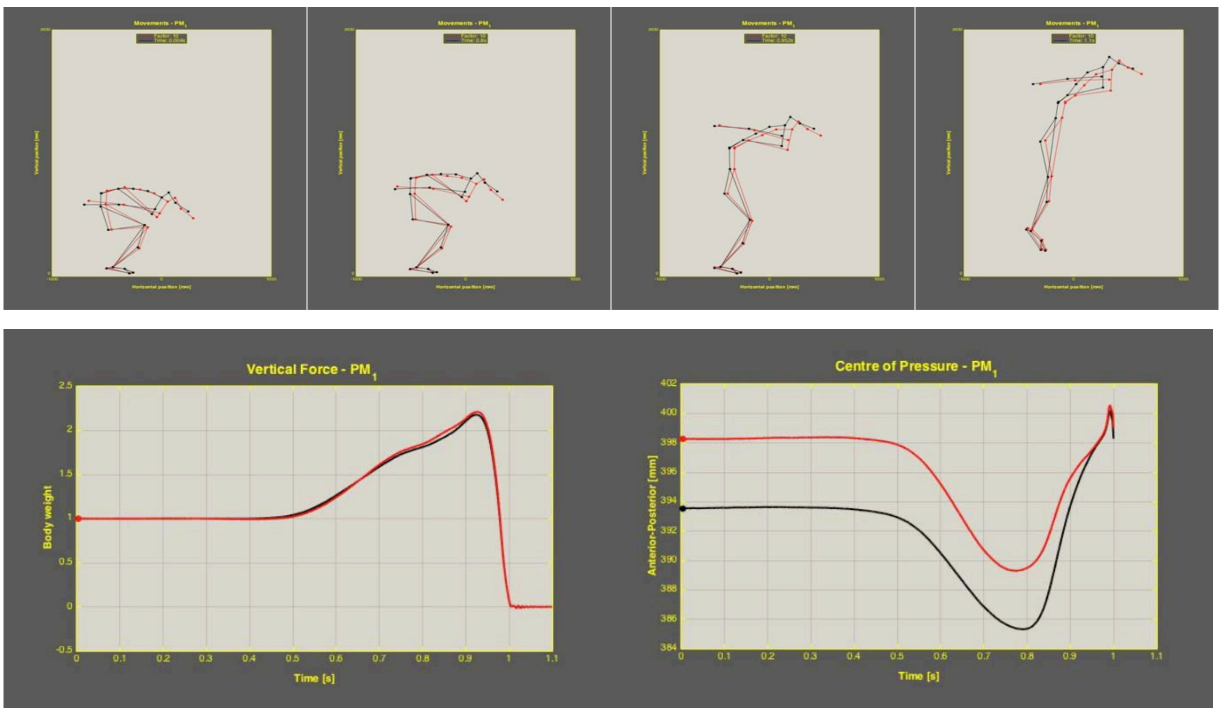


Figure 7. Change in posture, VertF and COP quantified by a positive PM_1 sc_i amplified by factor 10. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

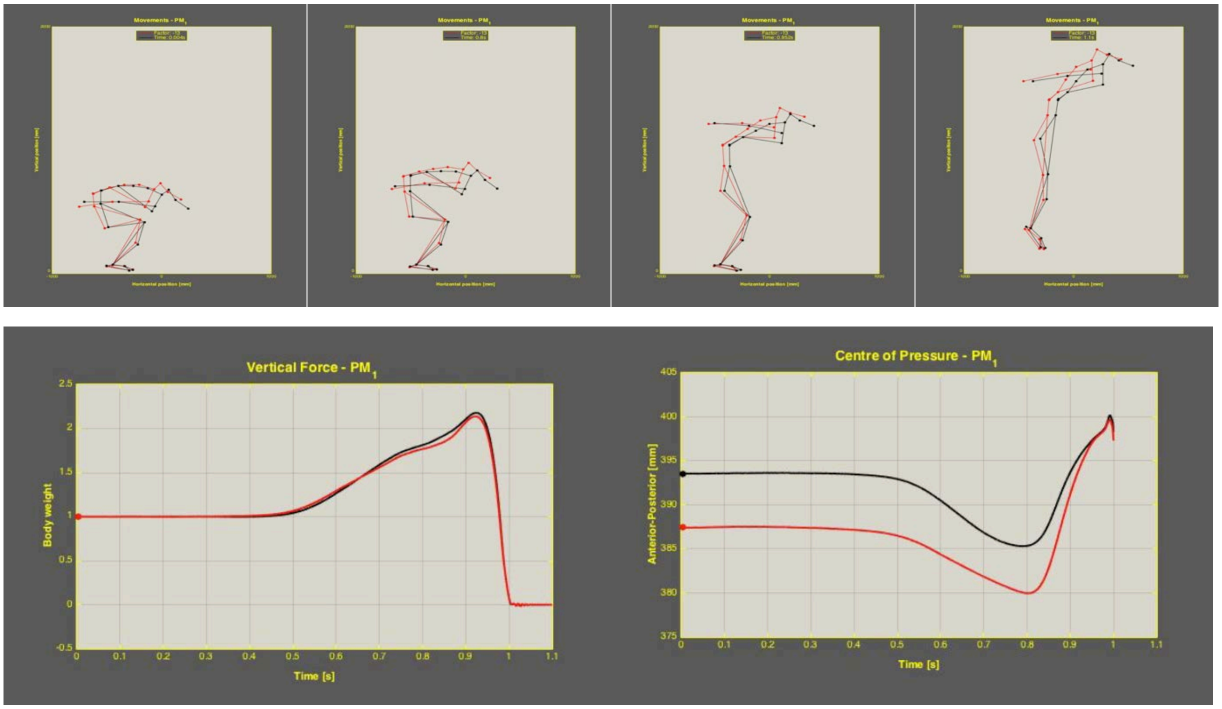


Figure 8. Change in posture, VertF and COP quantified by a negative PM_1 sc_i amplified by factor -13. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s

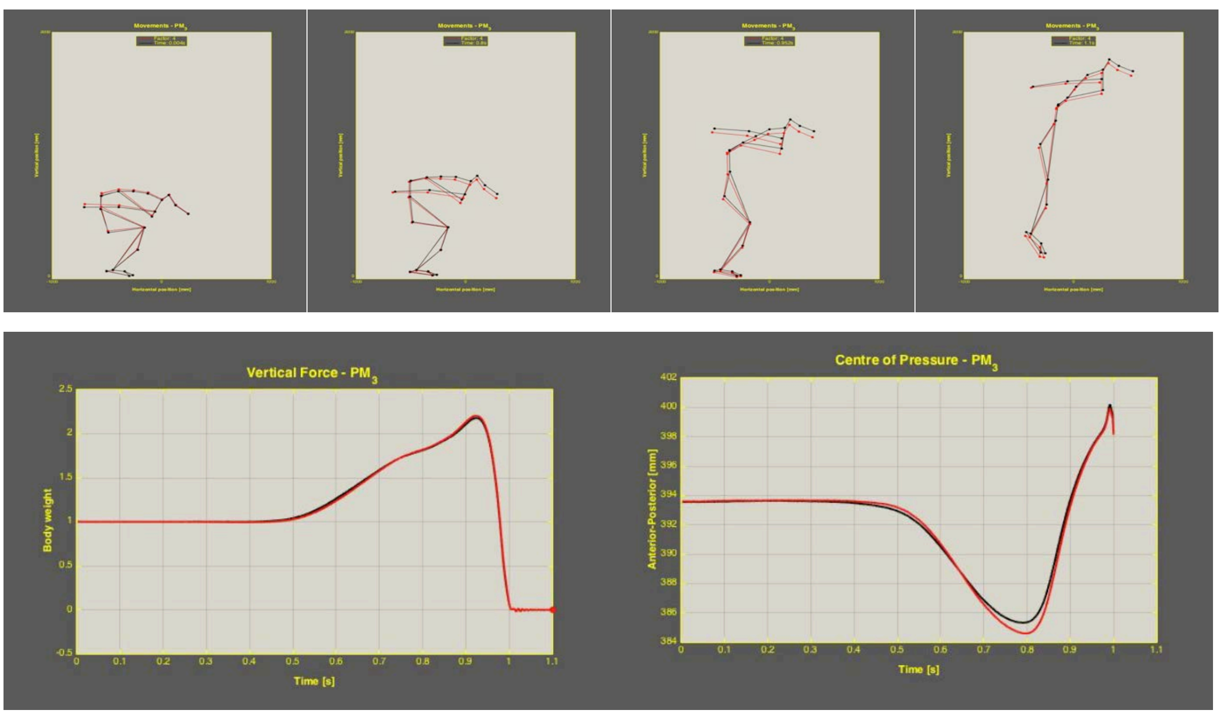


Figure 9. Change in posture, VertF and COP quantified by a positive PM_3 sc_i amplified by factor 4. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

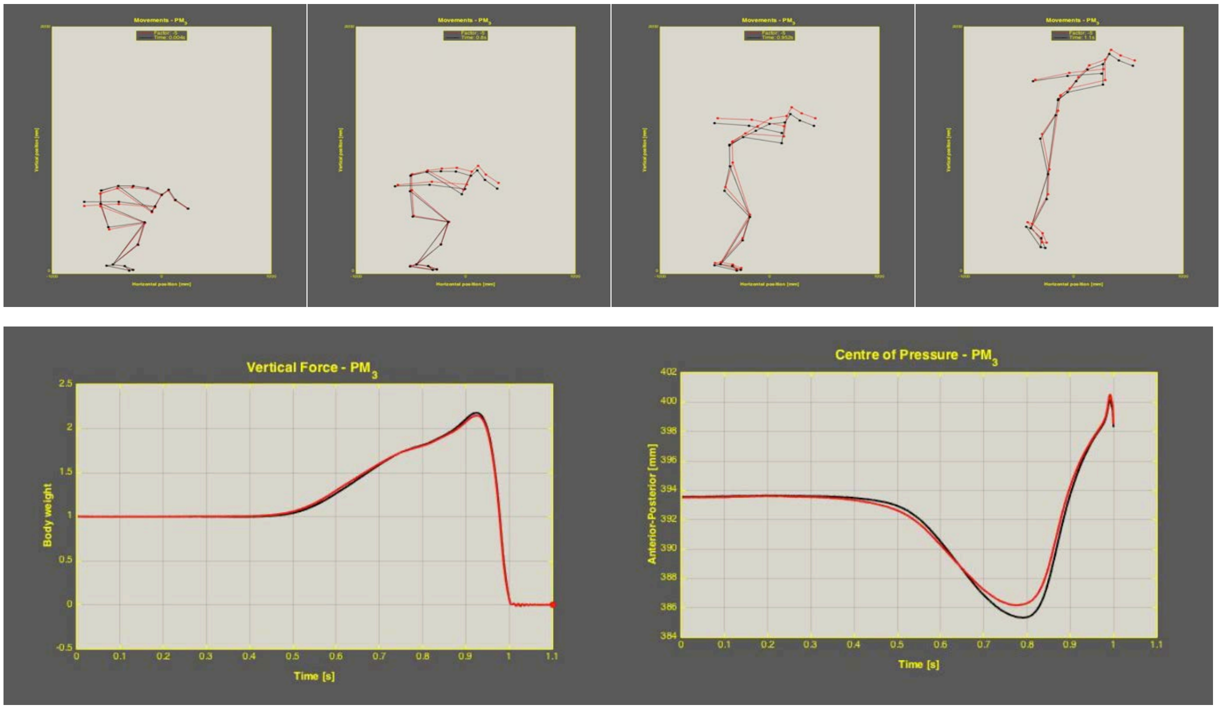


Figure 10. Change in posture, VertF and COP quantified by a negative PM_3 sc_i amplified by factor -5. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

4 Discussion

The present study investigated three main questions. Firstly, did ski jumpers interpret different take-off instructions similarly during imitation jumps? Secondly, what movement characteristics did these interpretations show throughout the take-off motion? Finally, do changes in sitting position and push-off kinematics affect kinetic variables? It was hypothesised that the jumpers would have similar interpretations of the instructions, and that the different conditions would relate to differences in kinetic variables. The findings suggest that the jumpers' overall interpretations of instructions are indeed similar, although some different interpretations were seen as well, and that the movement characteristics affect the kinetic variables. Ten principal movements (PM_k), covering 95.1% of the total variance in the take-off movement, were assessed and three distinct groups of movement characteristics were found. The first group, $PM_{1\text{-}2}$, represented 67.7% of the total variance and were anterioposterior (PM_1) and vertical (PM_2) whole-body movements throughout the take-off. We propose these as the 'inherent' movement variation in the take-off motion. The second group, $PM_{3\text{-}6}$, covering 23.9% of total variance, represented specific variations in both the sitting position and during push-off. These are proposed as ‘compensation’ movements during sitting position, and push-off. The final group, $PM_{7\text{-}10}$, consisted of distinct limb movements, upper body wave-like movements and compensations at the start of push-off. Together, they covered 1.9% of the total variance, and are proposed to be ‘perturbation’ movements from the activation of the push-off force production. Vertical force production (VertF), centre of pressure (COP) were the kinetic variables related to the *PMs*. The main findings suggest that the three distinct types of movement characteristics could be observed in the different patterns of the kinetic variables as well. VertF gave indications that both a lower and a more posterior sitting position had lower peak force and took longer to execute, while the opposite was seen in a more anterior and high position. The COP patterns supported the movement characteristics observed during the sitting position, and together with VertF distinguished the compensation movements during push-off from the initial sitting positions

4.1 Interpreting principal movements

To avoid misinterpreting the spectre of *PMs* it is vital to assess them together. A PCA is a decomposition process of an entire movement, not an analysis of already separated components; therefore, some PMs will be related and others not. Moreover, the eigenvalues (eV_i) indicate how meaningful the *PMs* are for the total variance, and hence how much weight they should have when relating to other *PMs*. This is why in our study $PM_{7\text{-}10}$ are presented with caution, because combined they represent less than 2% of total variance in a data set covering 95.1% of the total movement variance; some may be related to the *PMs* in the compensation group, but some could also be due to noise in the data set. Another source of misinterpretation could come from understanding the positive or negative variance as either only offensive/high or defensive/low movements, especially in non-cyclic and dynamic movements such as the take-off. As mentioned earlier, the scores (sc_i) of each PM_k reflect in which trials the main variance is observed, and in the take-off movement the dynamic push-off will contribute more to the overall variance than the static sitting position. Simply looking at the sc_i will not be enough to characterise the entire movement from start to finish. One could also question the lack of formal statistical testing of the results. However, presenting e.g. p-values of the different *PMs* to the mean movement (which is not the same as a ‘perfect’ take-off), could paint a misleading picture of the importance of the individual PM_k[33]. The statistical power of the first group (67.7% of total variance) will be higher than for the second group (23.9% of total variance), but the practical significance of the second group might be larger in real life than for the first group. We are assessing distinct patterns, and great care is taken when presenting and interpreting the results, and drawing conclusions based on our findings.

4.2 Movement characteristics in a real take-off context

Ettema and colleagues (2005) wrote that when entering the take-off table at the end of the in-run, the jumpers are perturbed from having passed the kinetically demanding curved section. Doing nothing entering the curve and the centrifugal forces would leave the jumper in danger of a nosedive from the sudden break of the speed around the feet. Leaving the curve the opposite would occur, the feet now have greater speed than the upper body, and the jumper could end up landing on their backs. At the same time, the compressional forces take the normal force from lower than the gravitational force during the straight section before the curve, to higher by a factor of 1.8[7]. In other words, the curved section possibly leaves the jumper perturbed in two distinct ways. Firstly, the vertical variance seen in the movement characteristics in PM_2 could be affected from the compressional forces. This movement variance suggests that compression in itself would not necessarily negatively affect the COP; hence the balance, if managed through the curve, would allow for a well-directed VertF. Secondly, and somewhat more complicated, are the anterioposterior perturbations that could affect the initial sitting position before take-off, and this is why the 'compensation' group of $PM_{3\text{-}6}$ are interesting. A badly managed curved section would alter the COP in unwanted directions, and balance would be negatively affected. Leaving PM_4 out because of the unclear basis of its origin, the $PM_{3,\,5\text{-}6}$ sitting position could illustrate the consequences of being too offensive or defensive in $PM_{1\text{-}2}$ sitting position, and how this affects both the direction of VertF and the need to create a forward rotation to reach the flying position. The initial compensation in sitting position might not in itself be negative, but the danger of either over or under exaggerating the compensation movements through the push-off phase is what could be the difference between the best and second-best jumpers. Coaches will often use terms as 'too passive', or 'too eager' when talking about the take-off phase, and it is suggested that this is what we see in the push-off compensations. They can be categorised as either the jumper raising the upper body too quickly and stalling, or diving forward breaking the vertical lift. In other words, the horizontal movement aspects of the push-off compensations could be detrimental to both the need for optimal vertical lift and forward rotation. In addition, the compressional perturbations mentioned for PM_2 could also affect the anterioposterior movement variations, making the initial sitting positions in the 'compensation' group even harder to overcome. Coaches and athletes could help interpret, and possibly explain, these suggested consequences with their first hand experience from observing the perturbations from the curved section in actual jumps.

4.3 A cohesive picture of the whole-body movement during take-off

The different movement characteristics, and VertF and COP patterns observed suggest that Chardonnens (2013) call for a better understanding of the whole-body movements alongside the lower limbs is warranted. The different 'compensation' movements show interesting configurations between the articulation of the spine, and the lower limb joints configurations. The shifts in anterioposterior direction of the COP could be alterations due to changes only in the ankle joint, but probably also further up the movement chain; the different configurations of the pelvis and upper body on top of these shifts in COP could suggests movement variations occur that would be meaningful for coaches and athletes to understand. Another aspect is the fact that the variations might not only be a consequence of the perturbations from the curved section, but also because of flexibility issues. If coaches and athletes know of differences in flexibility in specifically ankle joints, pelvis (e.g. gluteus) and lower back, some of the 'compensation' movements could help in evaluating the consequences of these differences.

4.4 Limitations

There are two main limitations in this study. First, during the data collection several marker trajectories were covered from the cameras because of the coaches being in the recording area to catch the jumpers. Although this was dealt with through a gap-filling algorithm in MatLab, the quality of the gap-filling could be lacking. Even if great care was taken to choose the optimal correction settings and all trials were assessed visually, the kinematic data could be affected by the corrections. Second, PCA is a data driven rather than a variable driven analysis, meaning that all interpretations and views are subject to the behaviour of the data, and not to established standards. This means that the interpretations of the different *PMs* might be misleading, or even wrong. What movements are meaningful and how we separate noise in the data from actual movement variation are two examples of issues to overcome when analysing the movements. In addition, the kinetic data presented is only related to the *PMs*, so no causality can be established. On the other hand, the addition of the kinetics has been helpful in some aspects of analysing the movement characteristics, for example on the distinction of the ‘compensation’ movements in $PM_{3\text{-}6}$.

5 Conclusion

Overall the different instructions were interpreted similarly between jumpers.

Individual differences were observed in all principal movements, but not in a way that suggest a substantially different execution, from others.

Anterioposterior and vertical shifts, alongside tilts in the pelvis and upper body were the main variations observed in the sitting positions. These different variations correlated with specific changes in push-off movements.

For each variation described, correlated changes in kinetic variables were determined in the current study.

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Appendix

A.1 Assessment of jump variations – $PM_{1\text{-}10}$

The boxplots show the sc_i distribution (y-axis) in each condition (x-axis). The line graphs show individual sc_i (y-axis) of each jumper (x-axis) in each condition (colour).

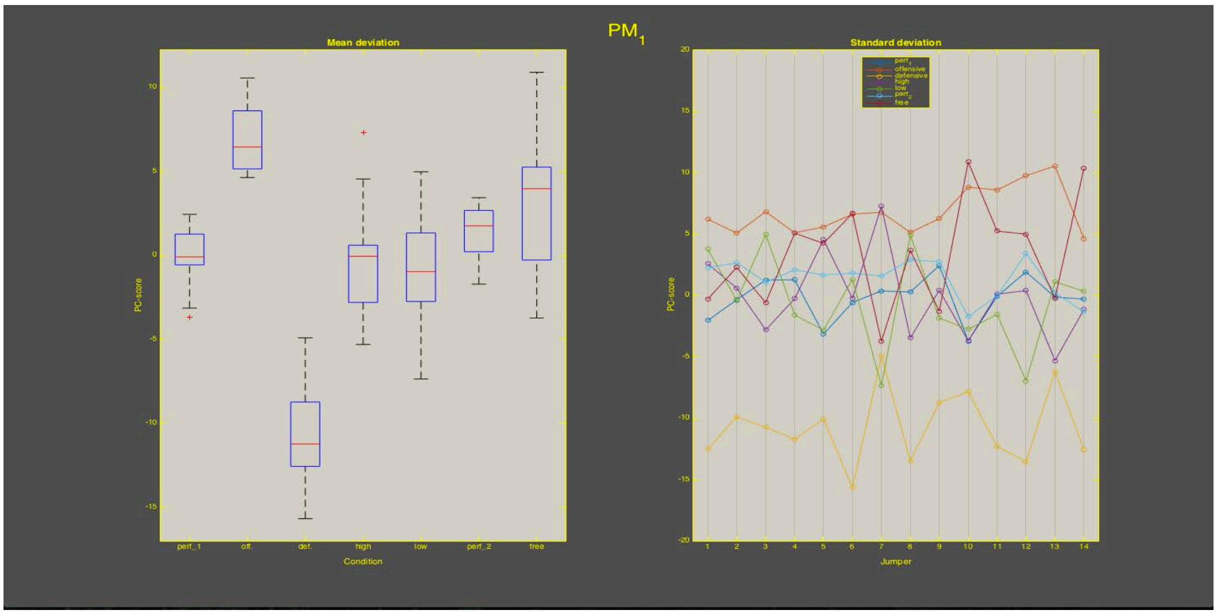

Figure 12. Distribution of sc_i for PM_1 over different conditions (left) and for individual subjects (right)

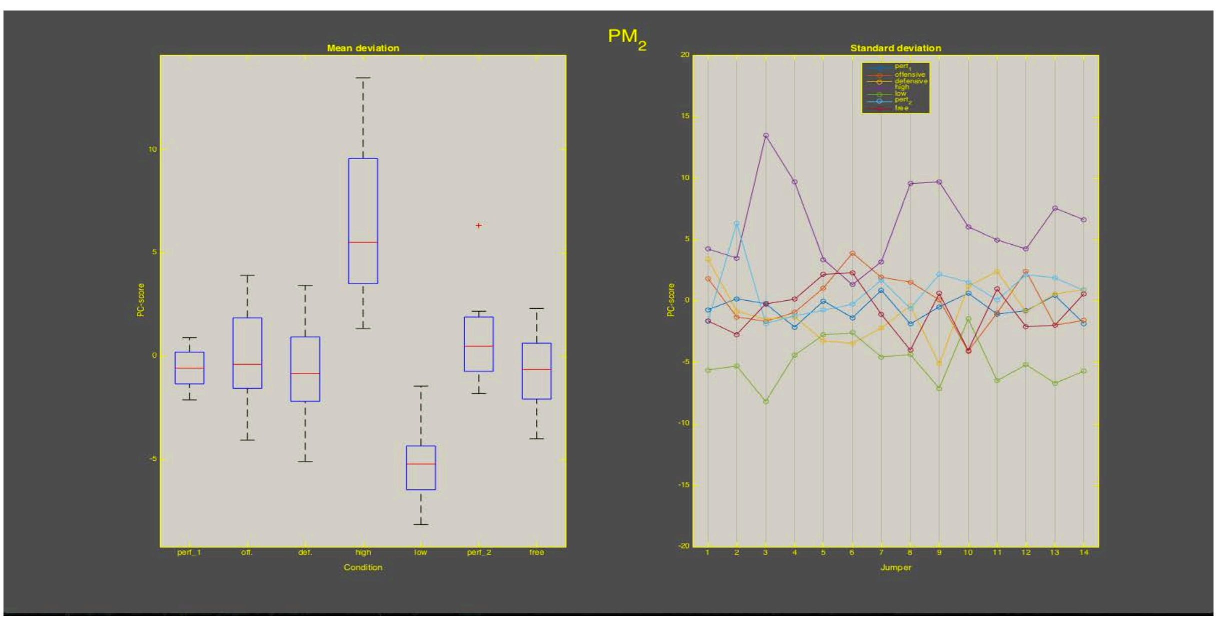

Figure 13. Distribution of sc_i for PM_2 over different conditions (left) and for individual subjects (right)

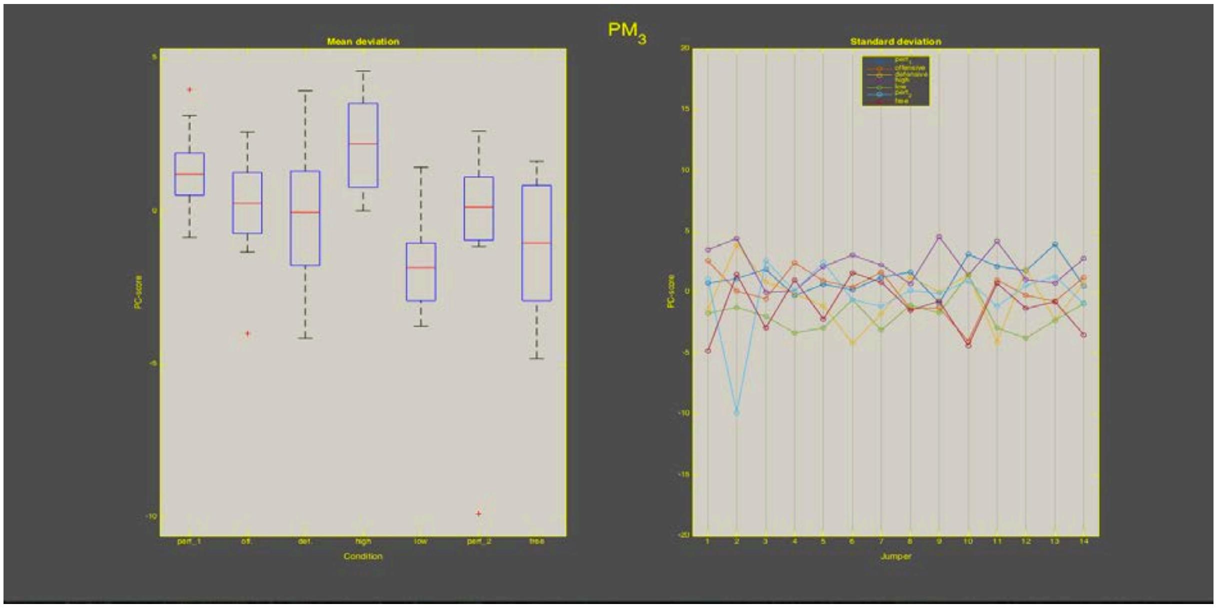

Figure 14. Distribution of sc_i for PM_3 over different conditions (left) and for individual subjects (right)

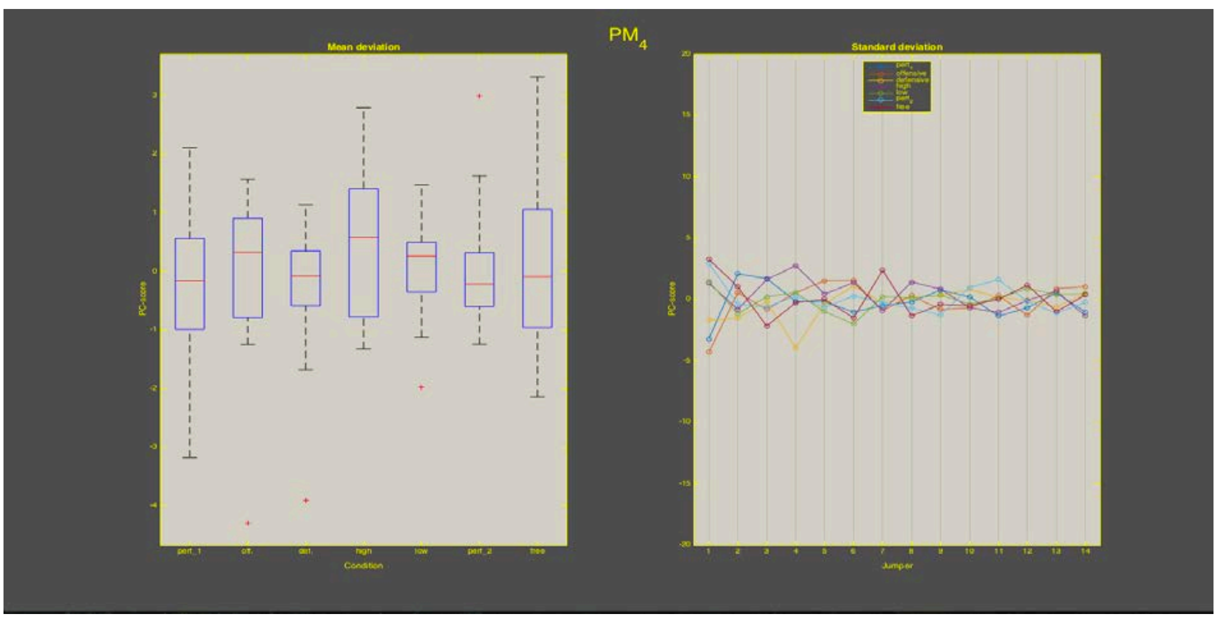

Figure 15. Distribution of sc_i for PM_4 over different conditions (left) and for individual subjects (right)

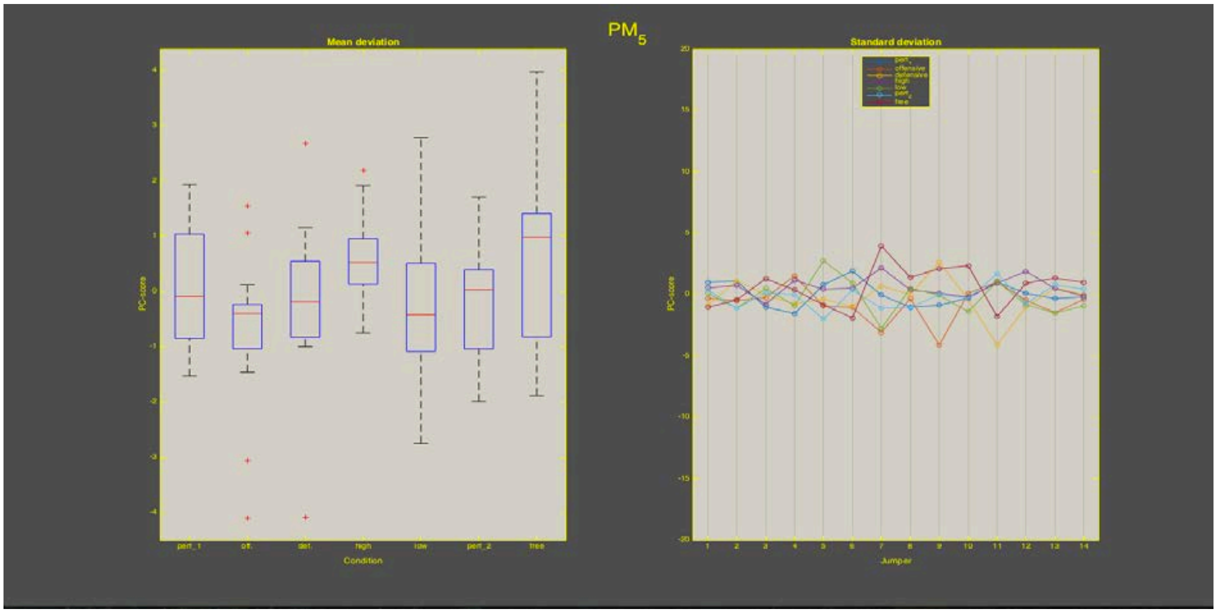

Figure 16. Distribution of sc_i for PM_5 over different conditions (left) and for individual subjects (right)

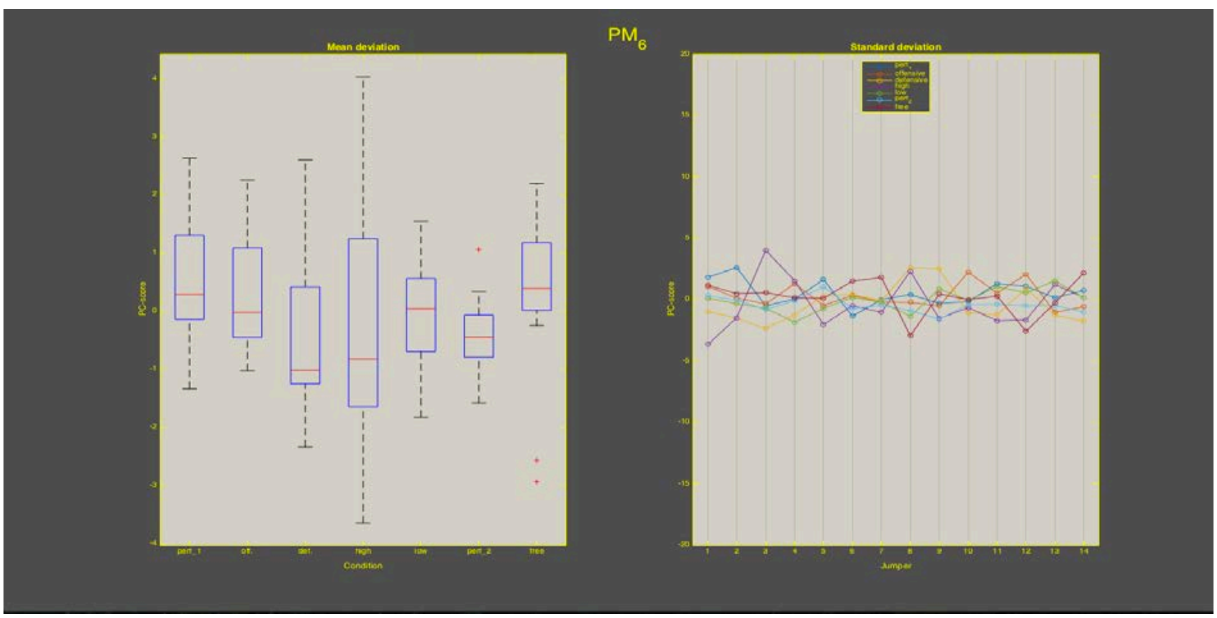

Figure 17. Distribution of sc_i for PM_6 over different conditions (left) and for individual subjects (right)

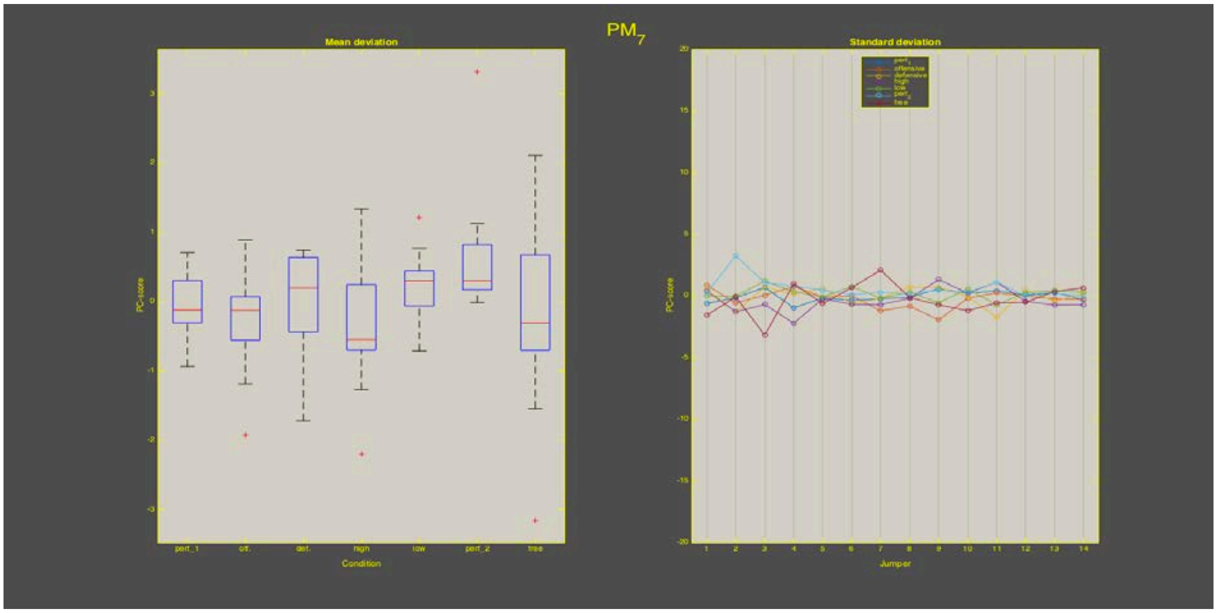

Figure 18. Distribution of sc_i for PM_7 over different conditions (left) and for individual subjects (right)

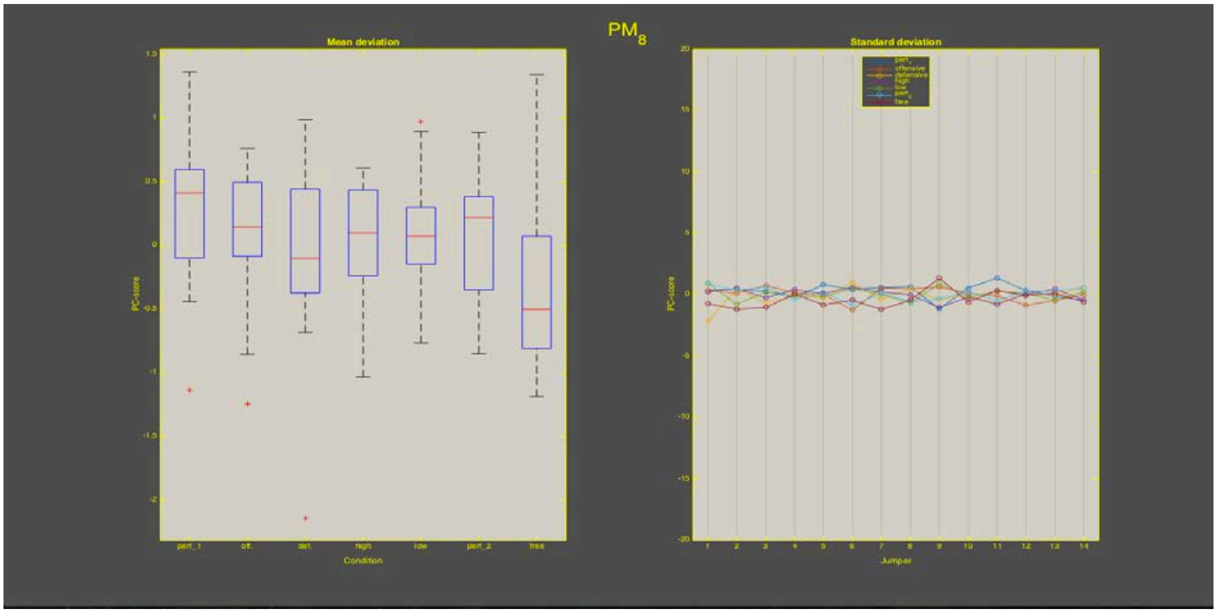

Figure 19. Distribution of sc_i for PM_8 over different conditions (left) and for individual subjects (right)

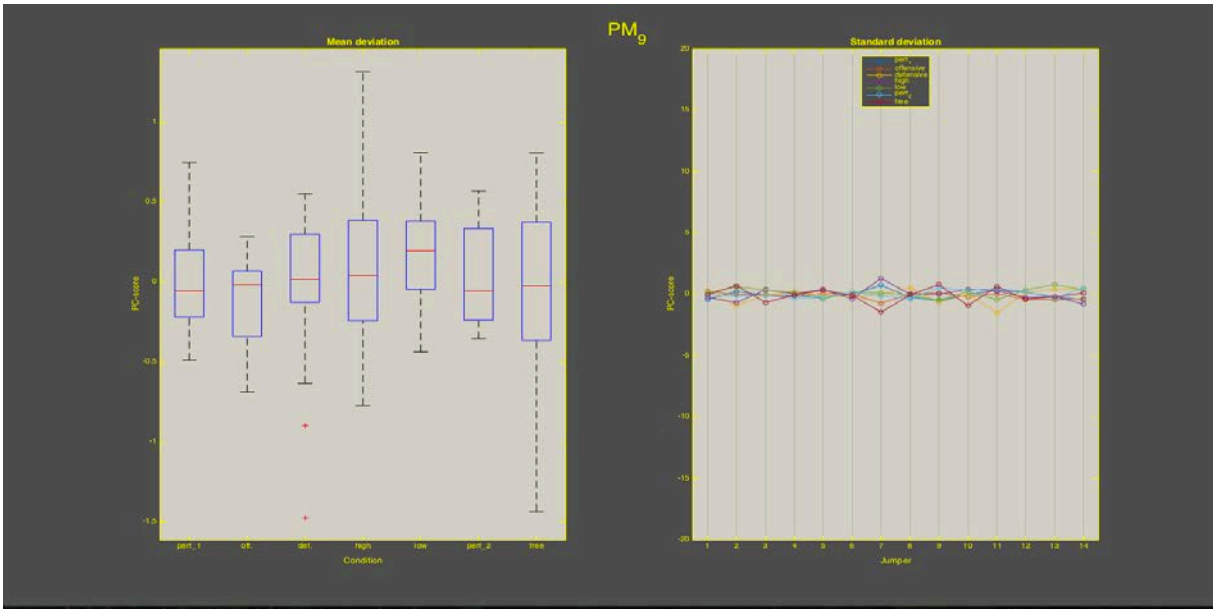

Figure 20. Distribution of sc_i for PM_9 over different conditions (left) and for individual subjects (right)

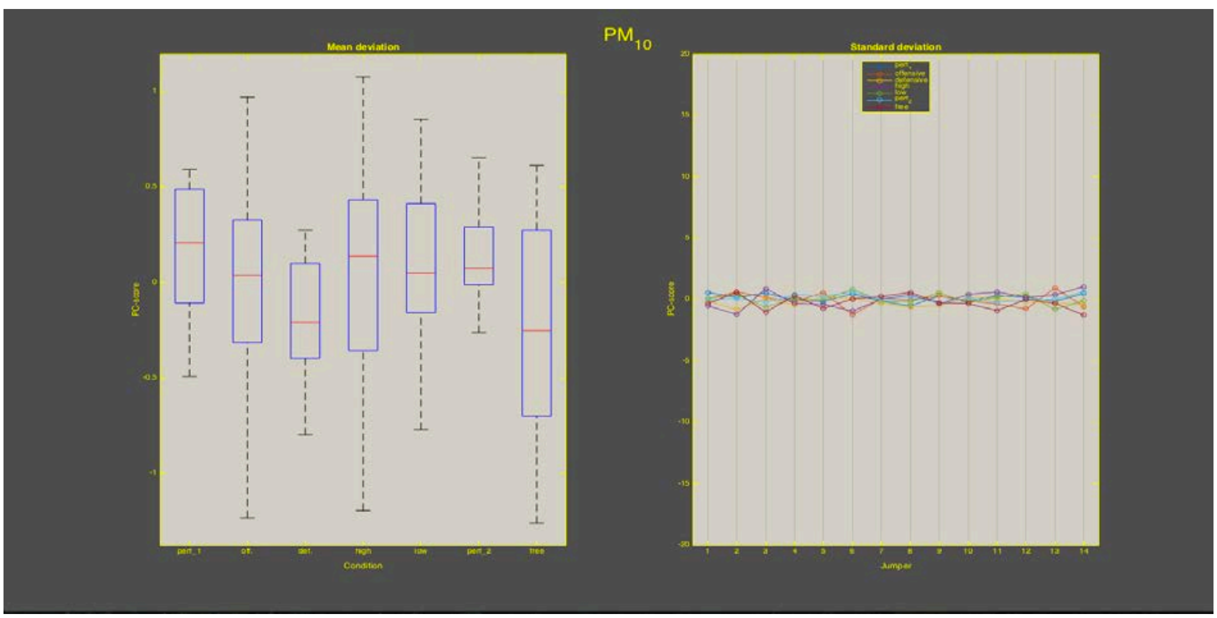

Figure 21. Distribution of sc_i for PM_{10} over different conditions (left) and for individual subjects (right)

A.2 Movement characteristics, vertical force production and COP – $PM_{1\text{-}10}$

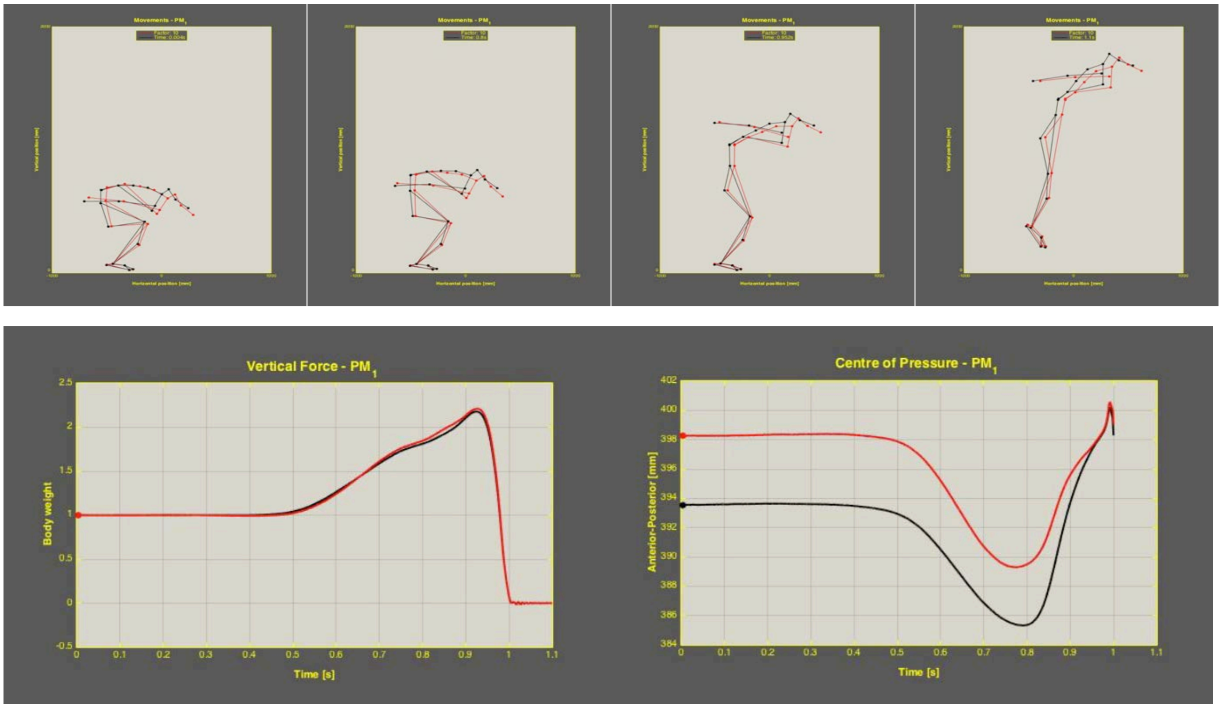

Figure 22. Change in posture, VertF and COP quantified by a positive PM_1 sc_i amplified by factor 10. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

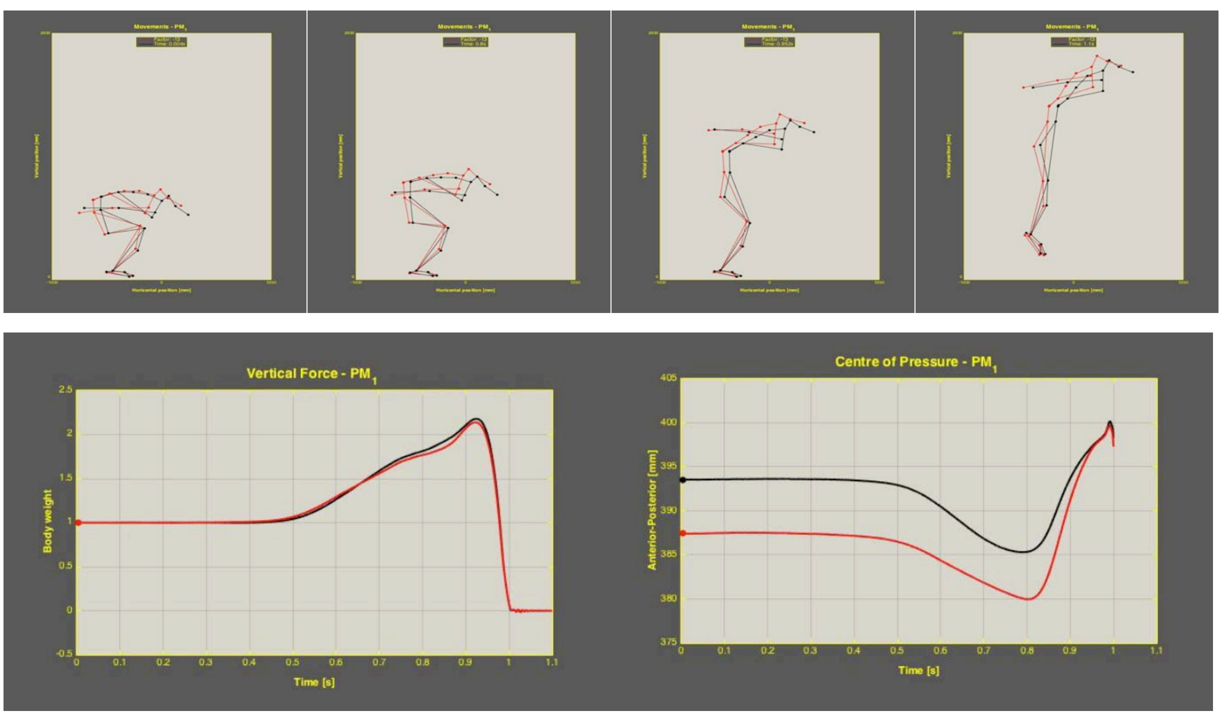

Figure 23. Change in posture, VertF and COP quantified by a negative PM_1 sc_i amplified by factor 13. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

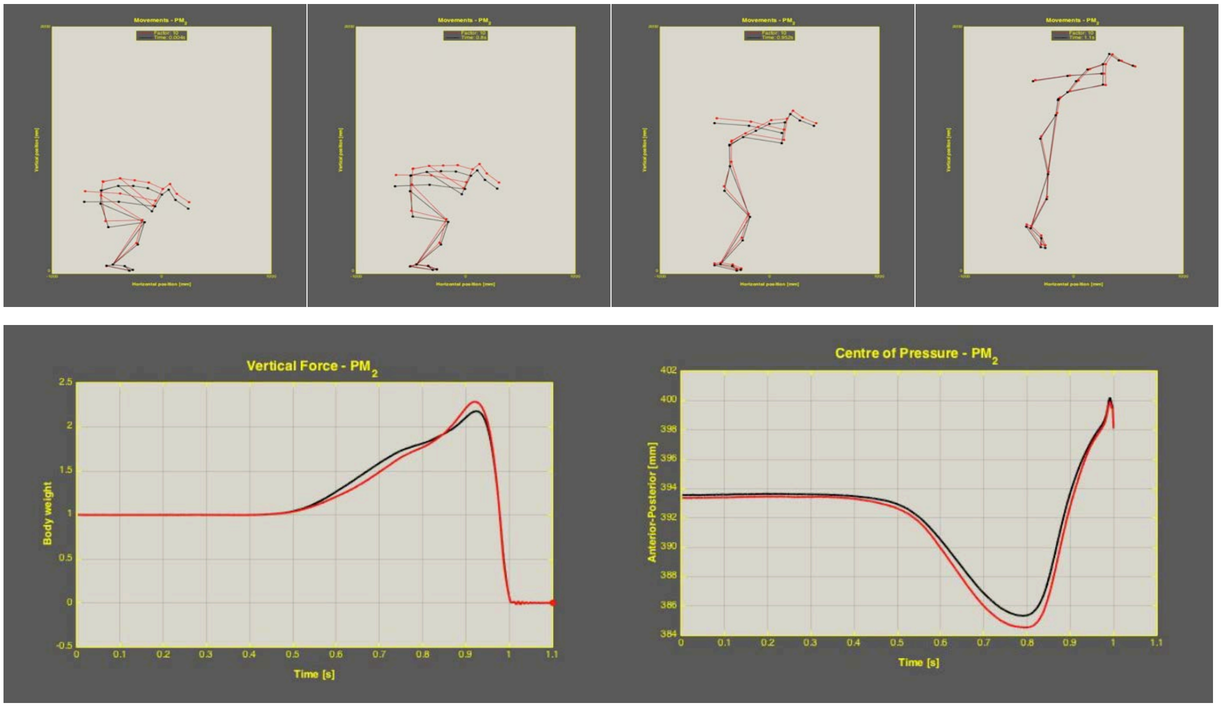

Figure 24. Change in posture, VertF and COP quantified by a positive PM_2 sc_i amplified by factor 10. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

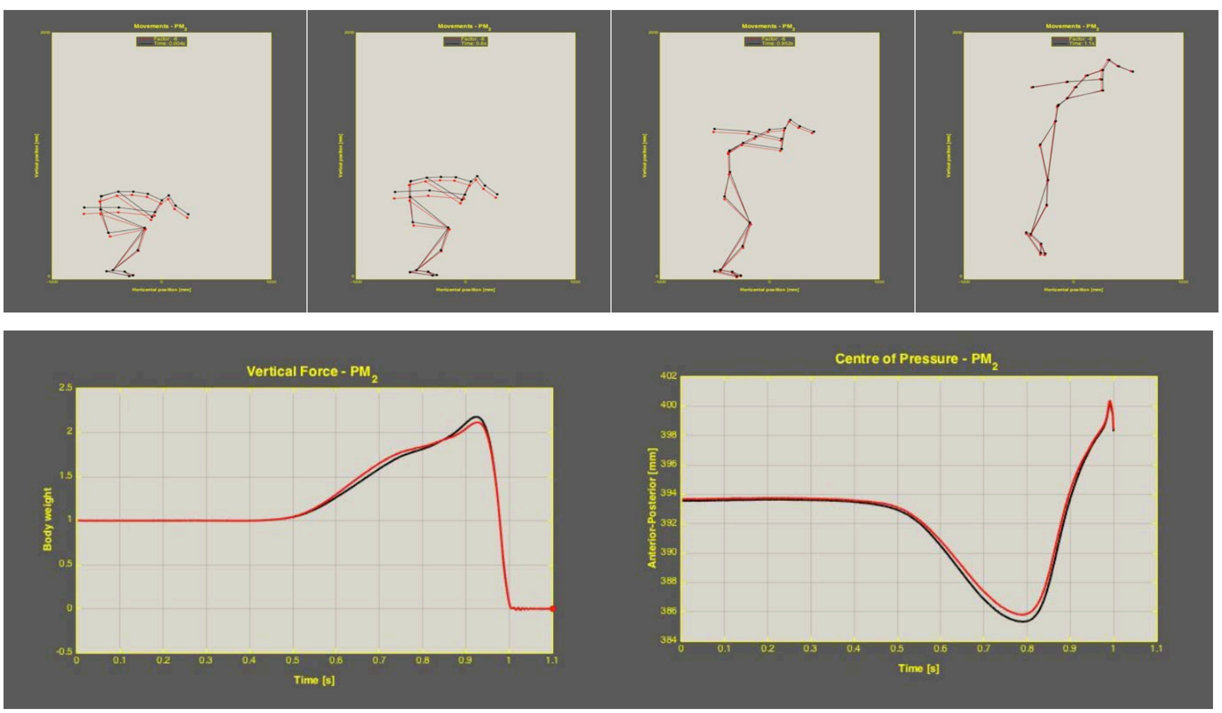

Figure 25. Change in posture, VertF and COP quantified by a negative PM_2 sc_i amplified by factor -6. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

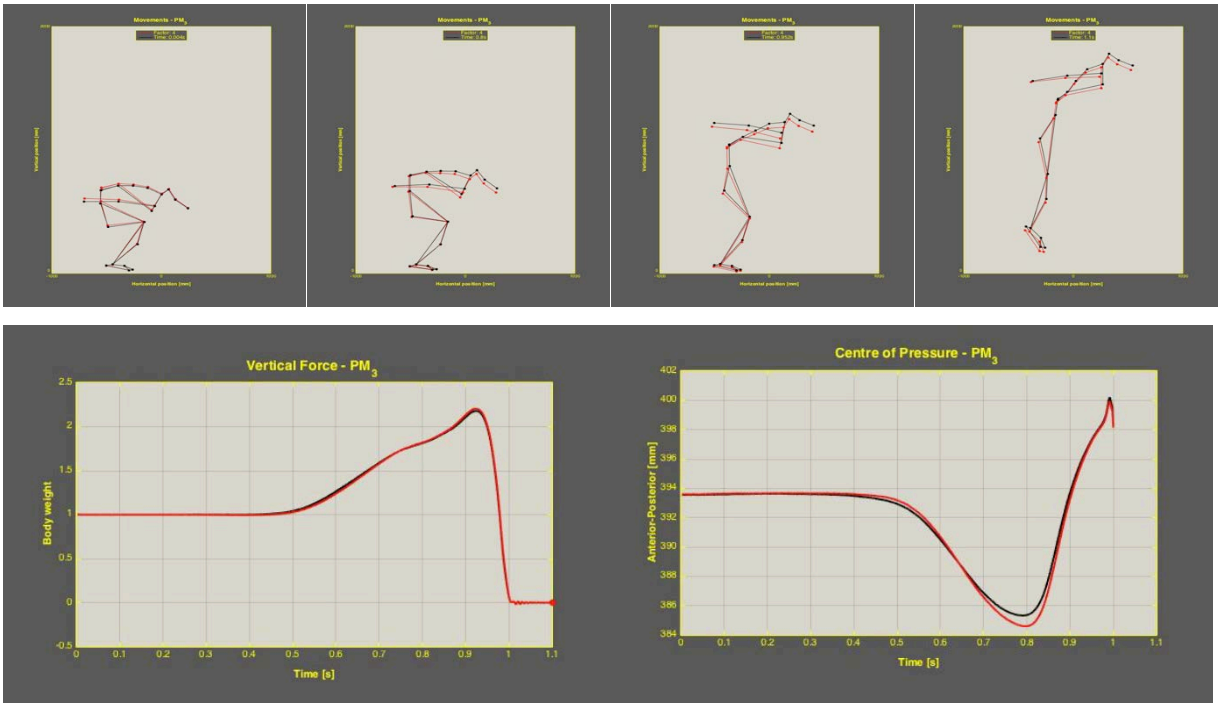

Figure 26. Change in posture, VertF and COP quantified by a positive PM_3 sc_i amplified by factor 4. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

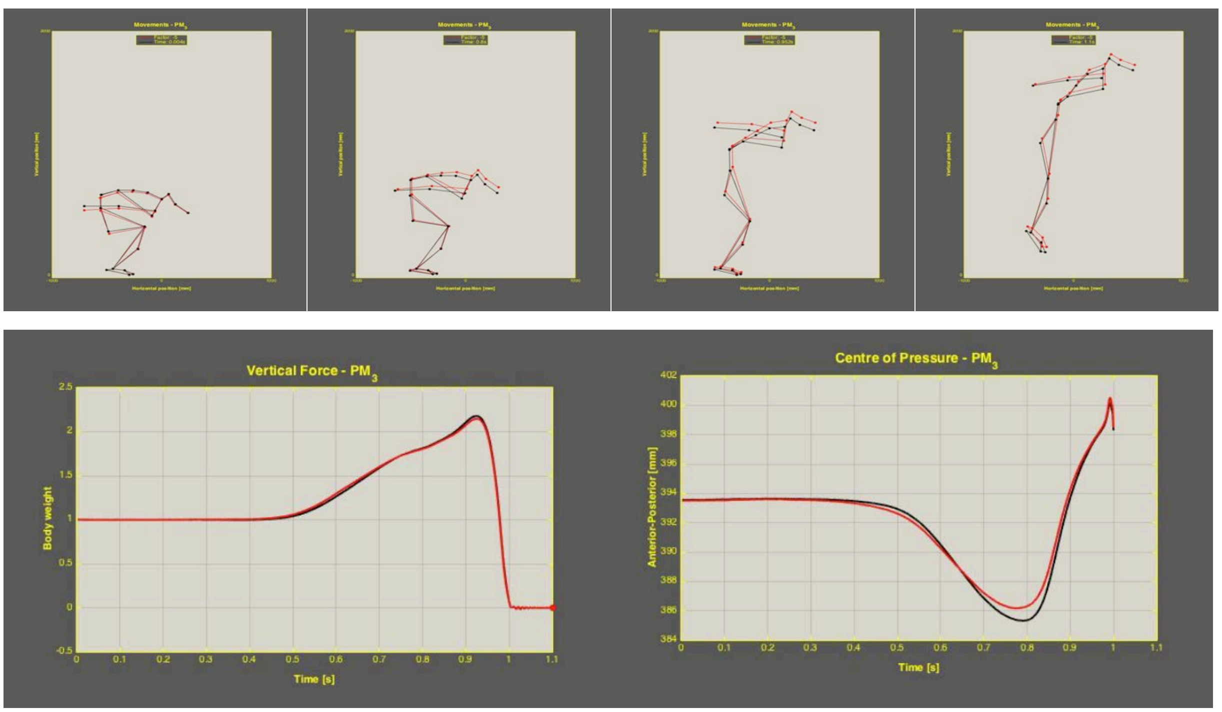

Figure 27. Change in posture, VertF and COP quantified by a negative PM_3 sc_i amplified by factor -5. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

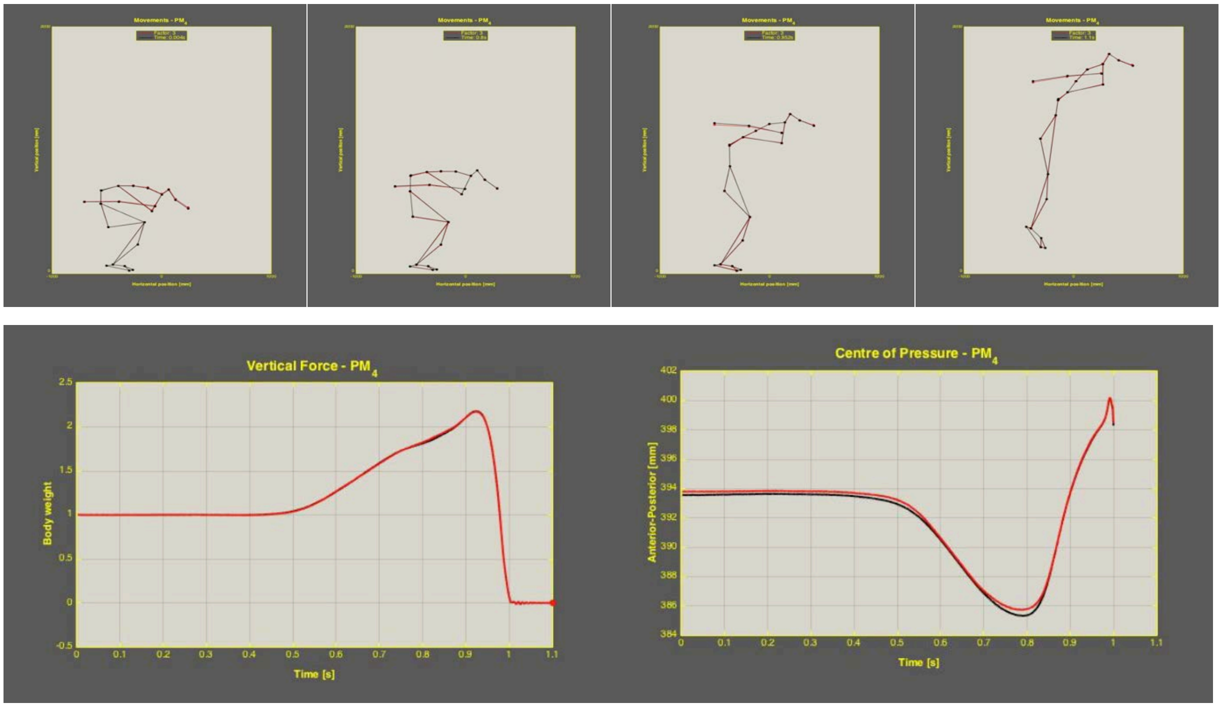

Figure 28. Change in posture, VertF and COP quantified by a positive PM_4 sc_i amplified by factor 3. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

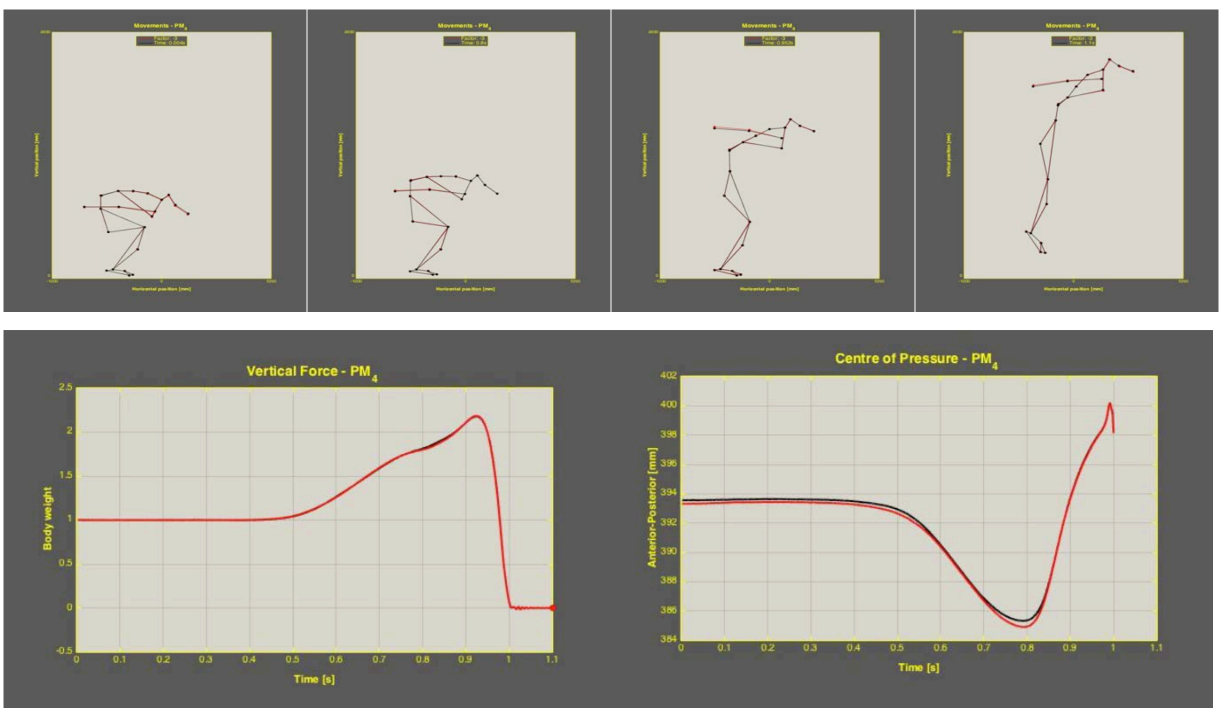

Figure 29. Change in posture, VertF and COP quantified by a negative PM_4 sc_i amplified by factor -3. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

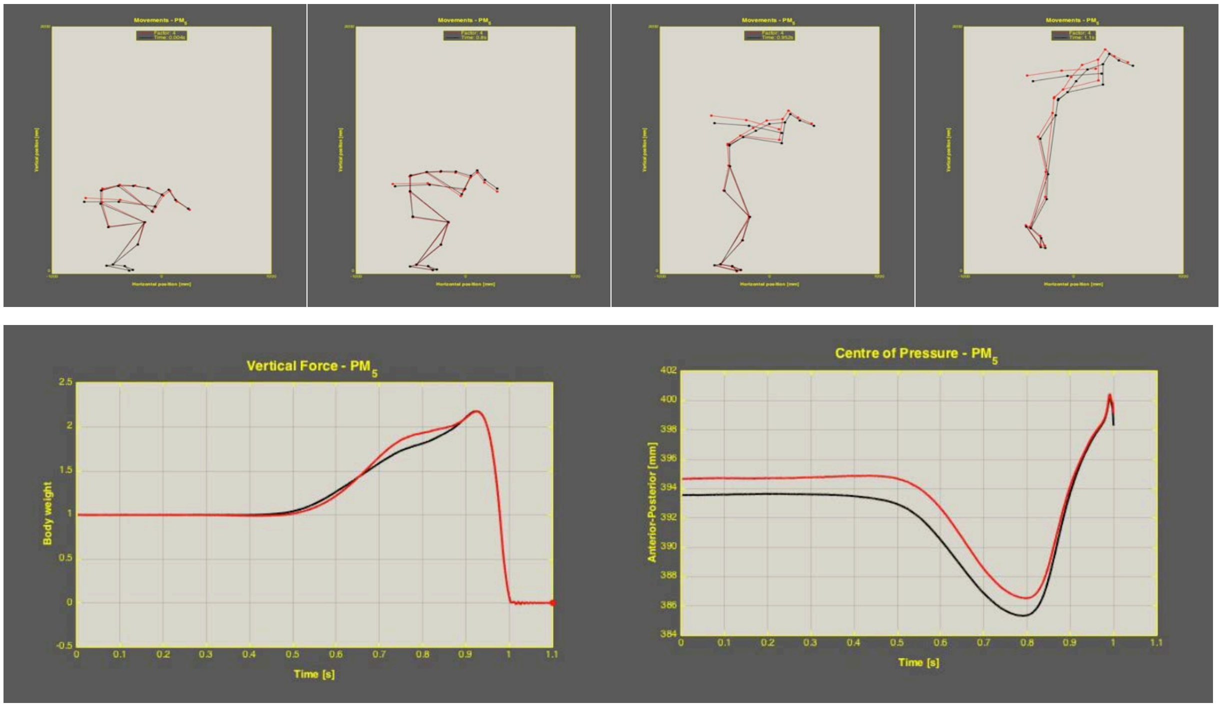

Figure 30. Change in posture, VertF and COP quantified by a positive PM_5 sc_i amplified by factor 4. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

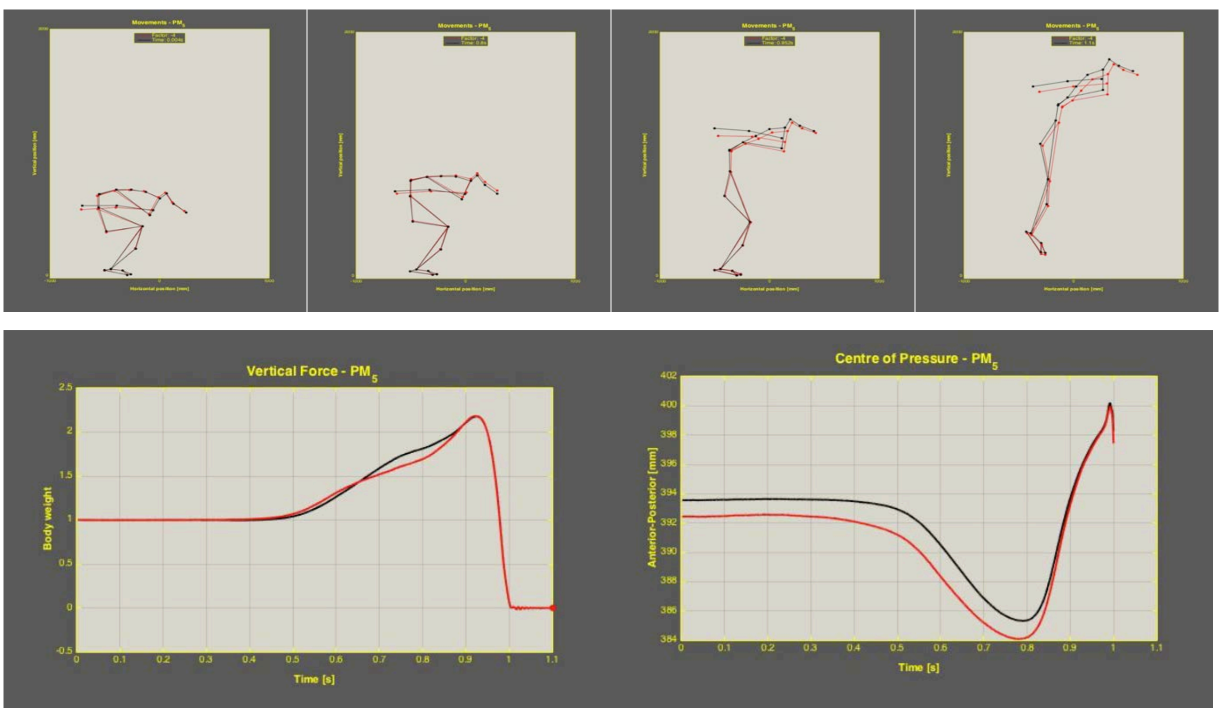

Figure 31. Change in posture, VertF and COP quantified by a negative PM_5 sc_i amplified by factor -4. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

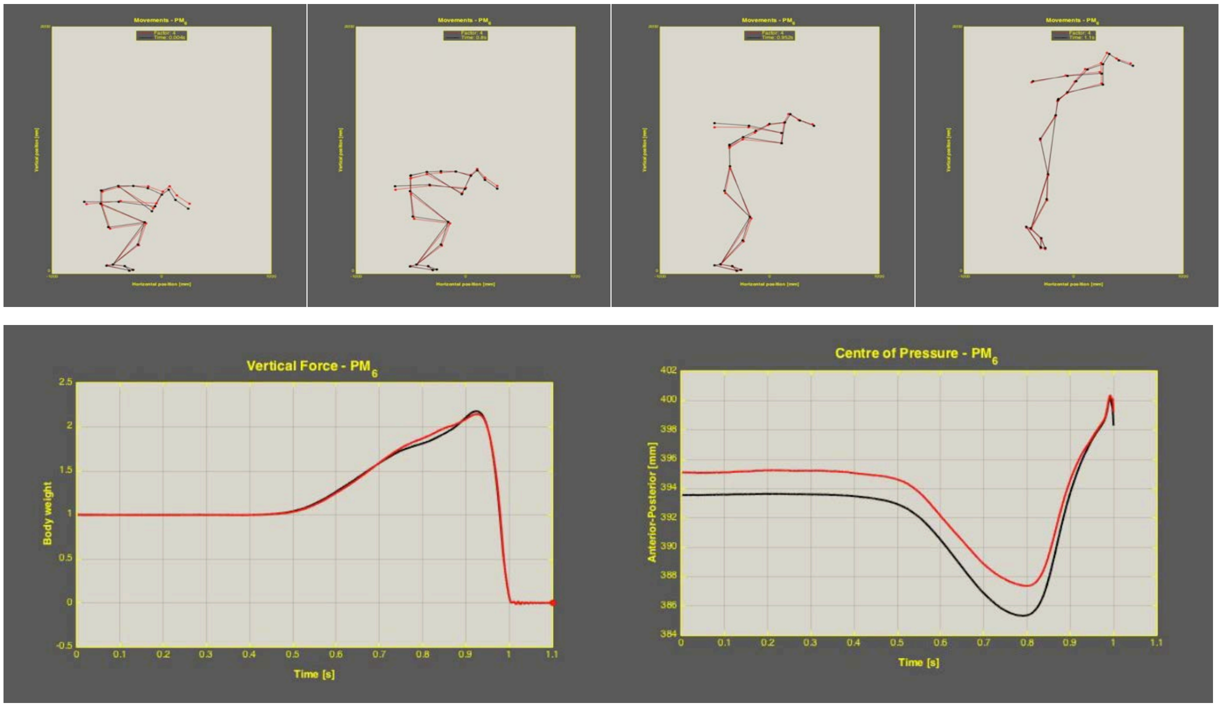

Figure 32. Change in posture, VertF and COP quantified by a positive PM_6 sc_i amplified by factor 4. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

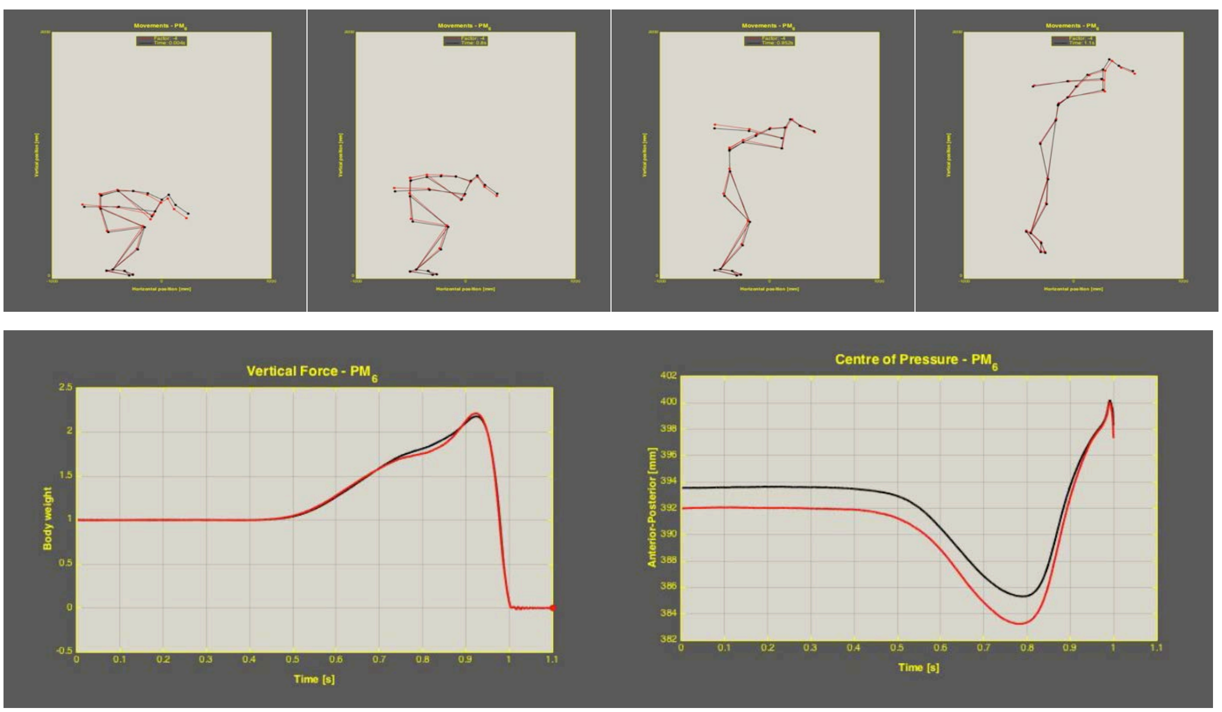

Figure 33. Change in posture, VertF and COP quantified by a negative PM_6 sc_i amplified by factor -4. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

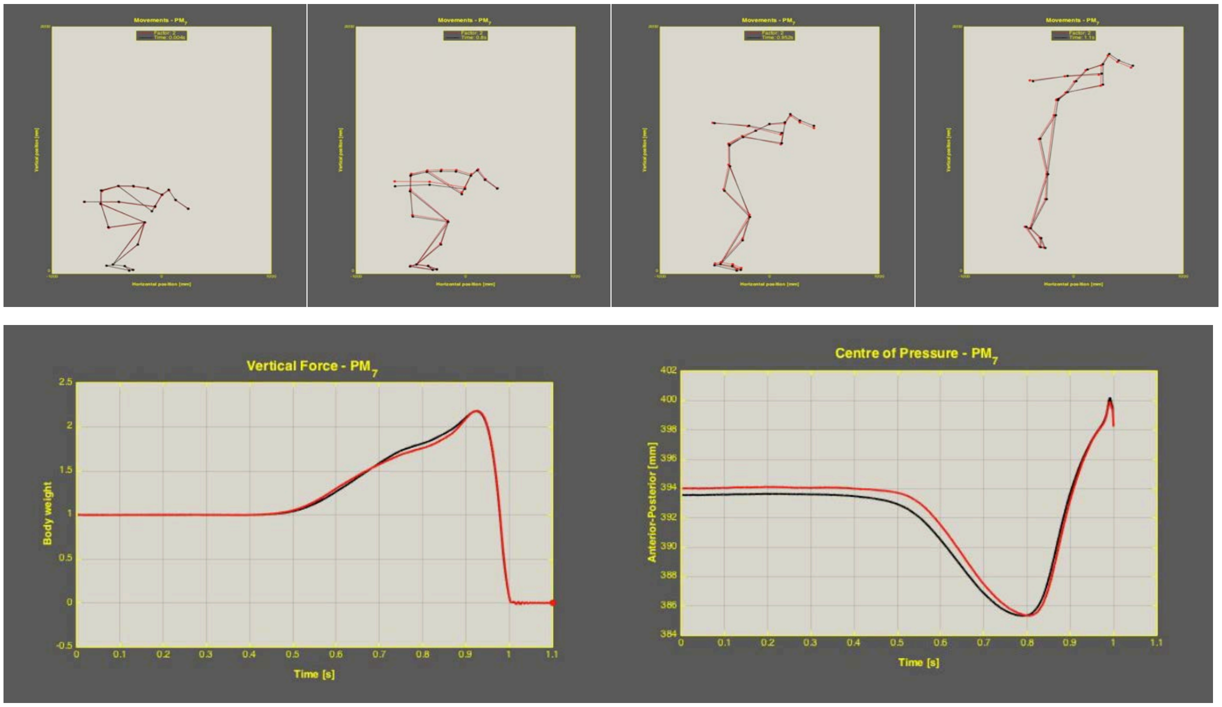

Figure 34. Change in posture, VertF and COP quantified by a positive PM_7 sc_i amplified by factor 2. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

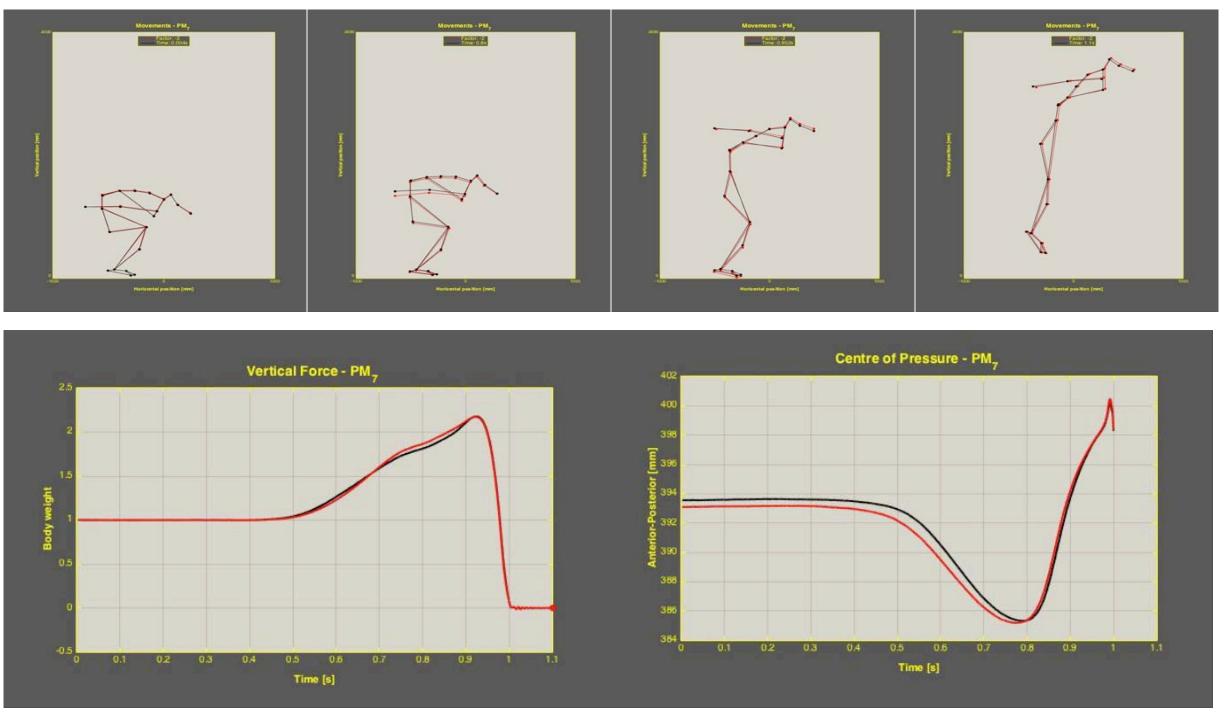

Figure 35. Change in posture, VertF and COP quantified by a negative PM_7 sc_i amplified by factor -2. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

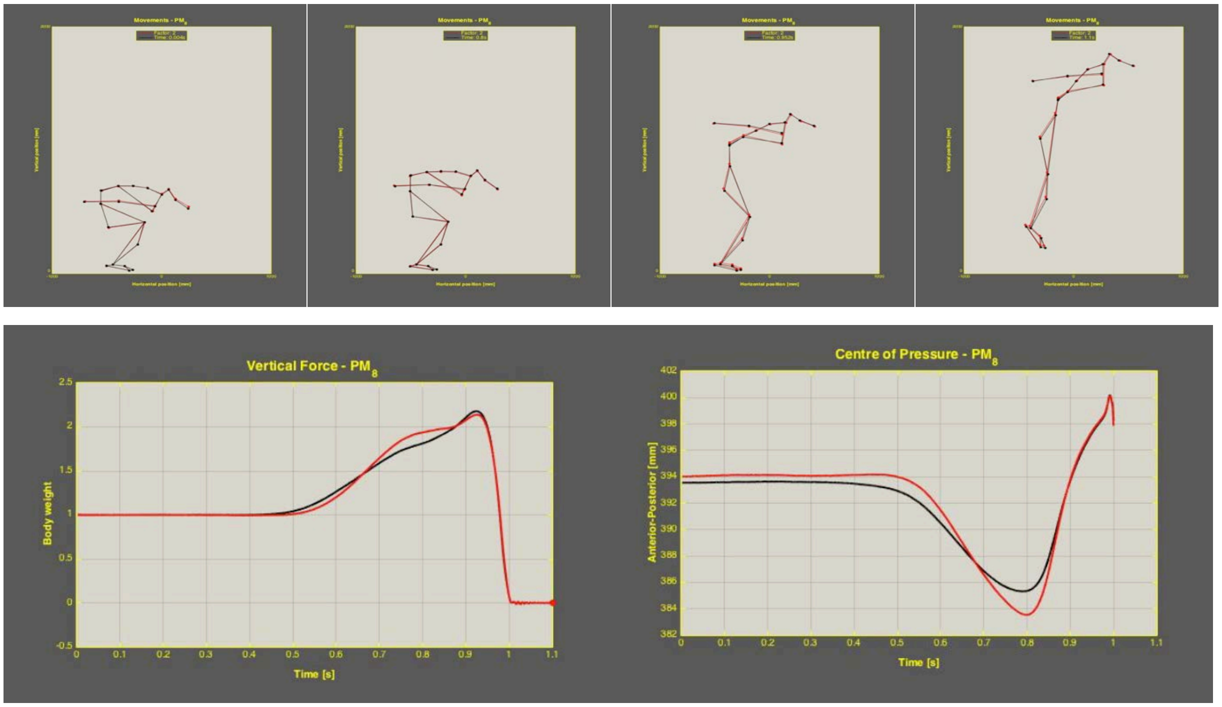

Figure 36. Change in posture, VertF and COP quantified by a positive PM_8 sc_i amplified by factor 2. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

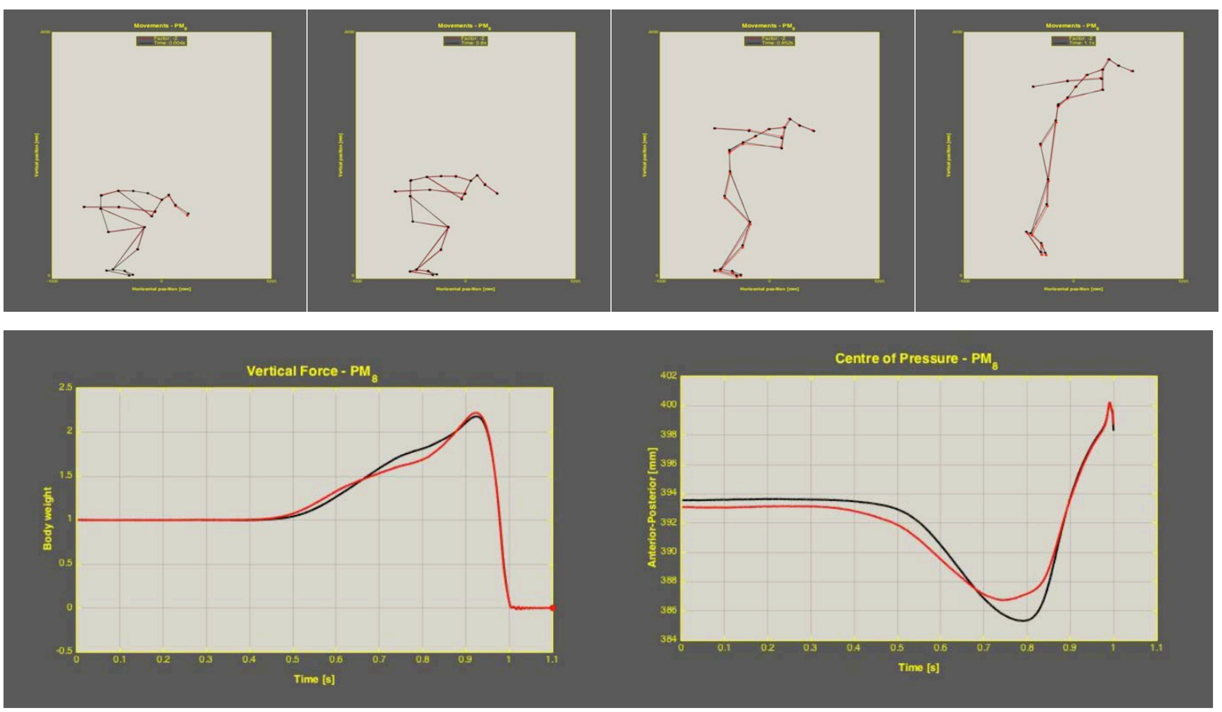

Figure 37. Change in posture, VertF and COP quantified by a negative PM_8 sc_i amplified by factor -2. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

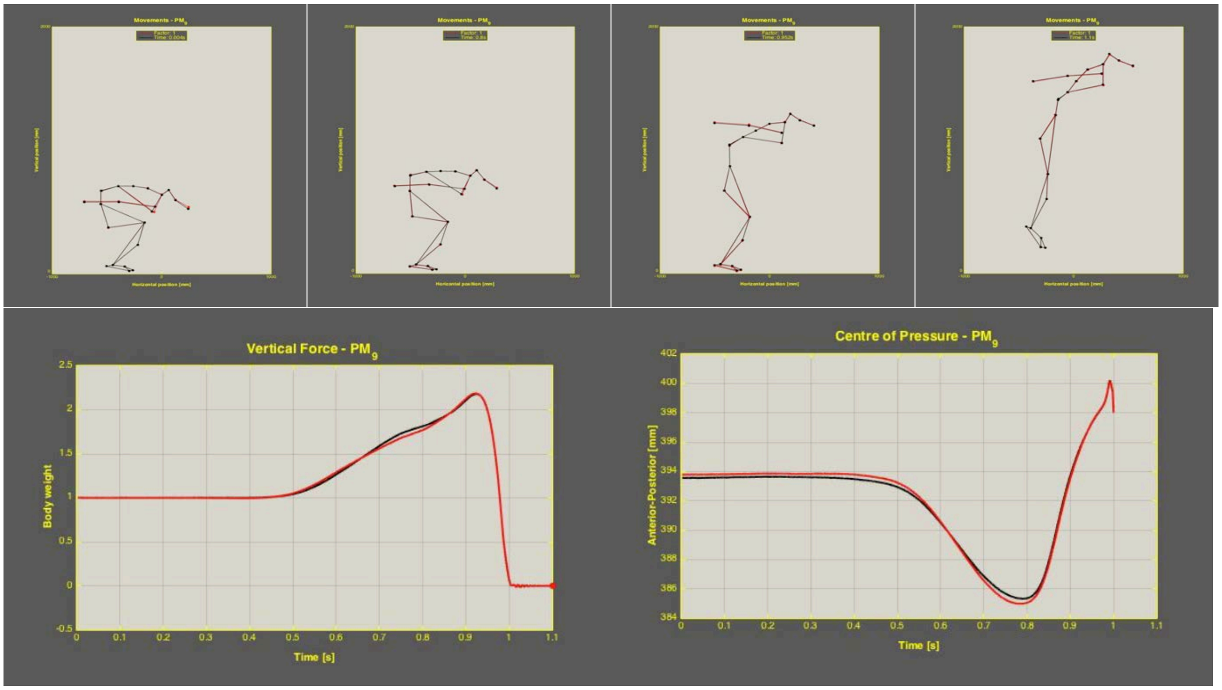

Figure 38. Change in posture, VertF and COP quantified by a positive PM_9 sc_i amplified by factor 1. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

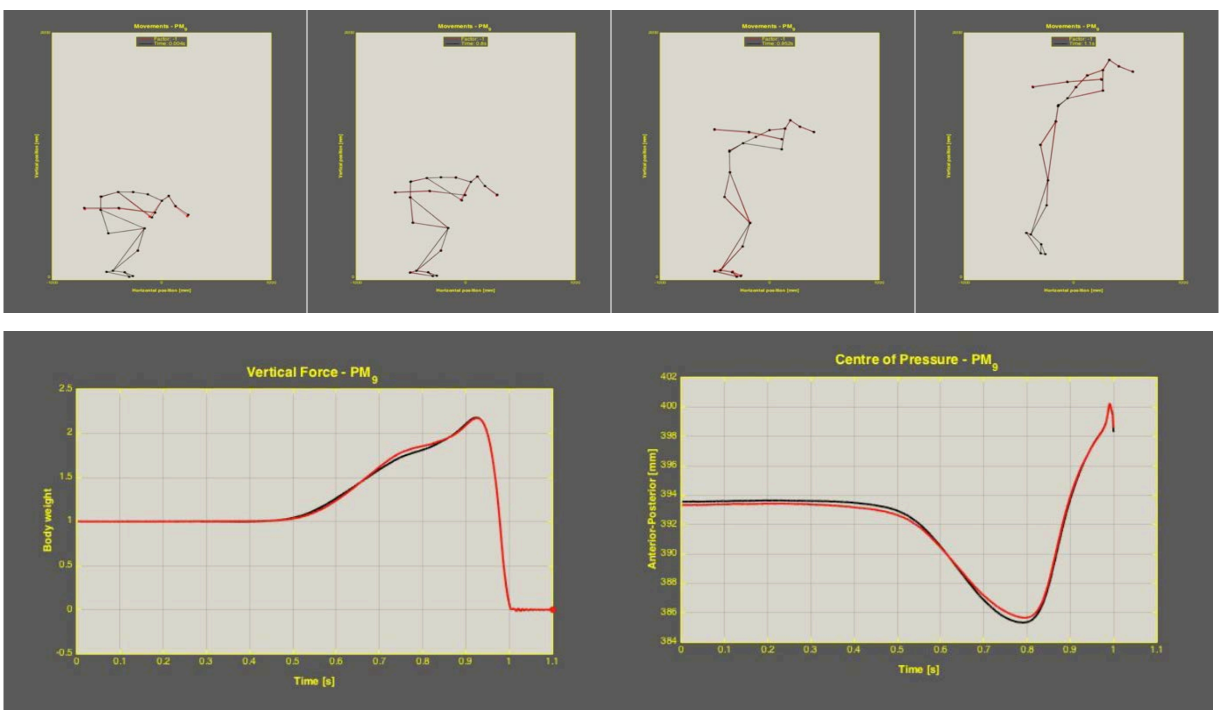

Figure 39. Change in posture, VertF and COP quantified by a negative PM_9 sc_i amplified by factor -1. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

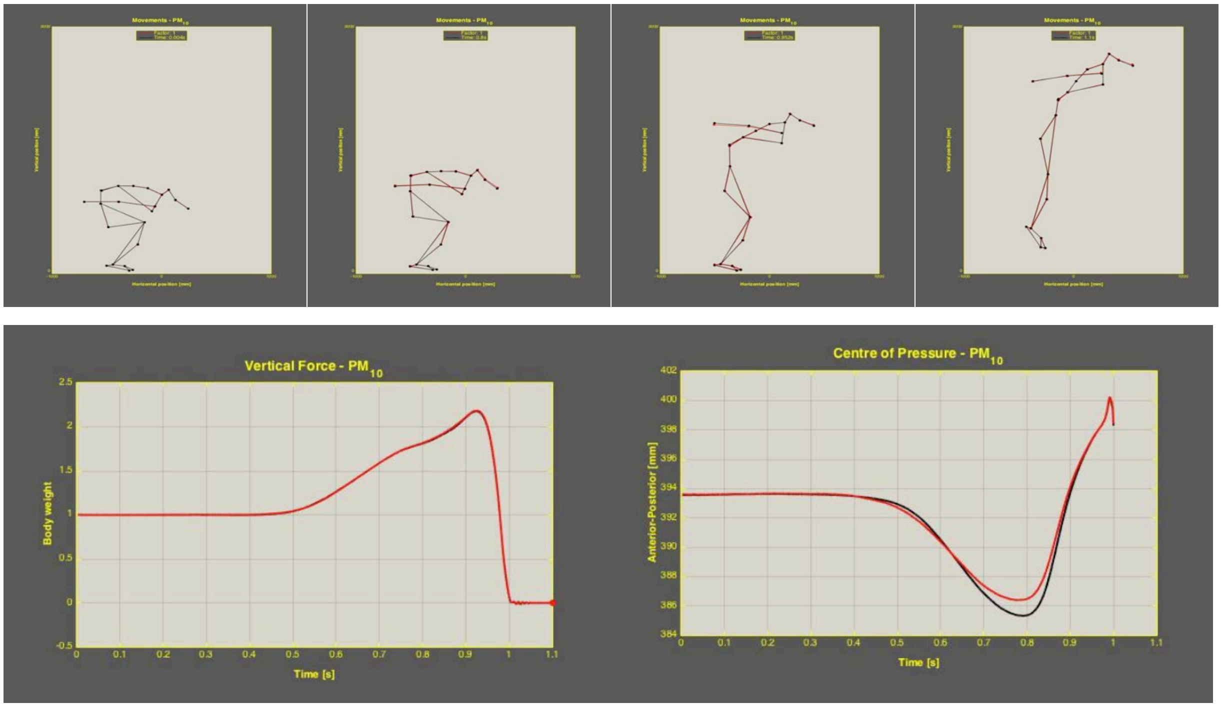

Figure 40. Change in posture, VertF and COP quantified by a positive PM_{10} sc_i amplified by factor 1. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).

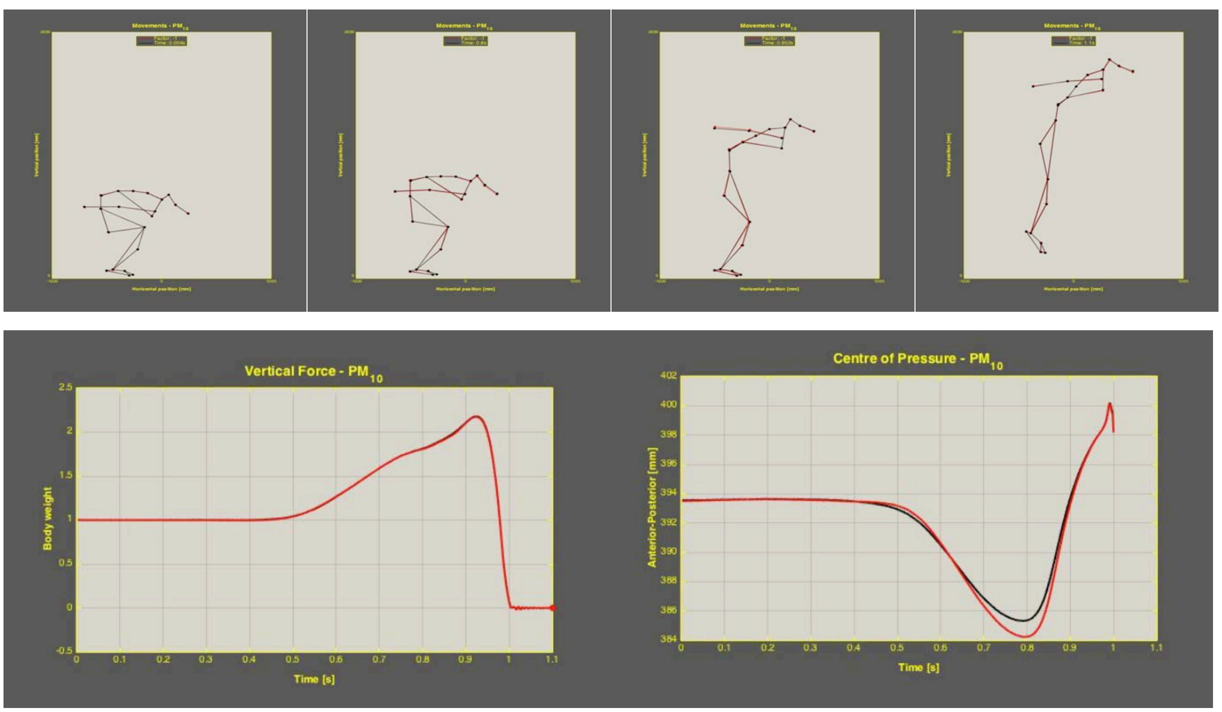

Figure 41. Change in posture, VertF and COP quantified by a negative PM_{10} sc_i amplified by factor -1. Black = mean, red = PM_k. Movement characteristics at 0.0 s, 0.8 s, 0.95 s, 1.1 s (top panels).