Imitation jumps in ski jumping: technical execution and relationship to performance level

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Abstract

Imitation jumps are frequently used in training for ski jumping. Yet, the dynamics of these jumps differ considerably. Thus, the relevance of imitation jumps for ski jumping performance is not elucidated. The aim of this study was to investigate the relationship between the technical execution of imitation jumps and ski jumping performance levels. We compared the imitation jumps of 11 ski jumpers of different performance level using a Spearman correlation transform of time traces of the kinetics (measured using force cells and motion capture) of imitation jumps. The kinetic aspects that were related to performance centred on the moment arm of ground reaction force to the centre of mass before the onset of the push-off, angular momentum early in push-off, thigh angle during the main period of push-off and vertical velocity towards the end of push-off. We propose that the thigh angle may be a key element allowing high development of linear momentum, while preparing for appropriate aerodynamic position. Furthermore, the findings suggest that the kinetic development prior to (and during) push-off is more important than the kinematic end state at take-off.

Keywords: ski jump; imitation; biomechanics

Introduction

Because of the nature of the sport, in ski jumping, indoor imitation jumps are frequently used in training. The main reason is that the number of repetitions that can be made in a jumping hill within a reasonable time is very low (about four jumps per hour). Moreover, imitation jumps allow quick feedback on the quality of the execution. Nowadays, force platforms are used to provide detailed information about the dynamics of the jump. In imitation jumps, the focus is directed not only to the movement outcome, but also to the control of dynamics leading to this outcome: it is well accepted in practice that both linear and angular momentum at take-off are essential for performance (see Ettema et al. 2016; Schwameder 2008). The linear momentum in the jumping hill can only be generated perpendicular to the hill floor, and thus depends on force generation perpendicular to the surface. The angular momentum to be generated should be small (but not non-existent) and allows an effective movement from the tucked in-run position towards a typical body configuration in the early flight phase (e.g., Schwameder 2008). This movement, i.e., rotation, is executed by obtaining a small moment arm (d) between push-off force and centre of mass (CoM) during (part of) the take-off action.

Because of different mechanical constraints (e.g., aerodynamics, ground friction), the dynamical details will be different in actual ski-jumping and imitation (Lorenzetti et al. 2019); Aerodynamic and friction forces create moments that affect the moments that the athlete needs to create actively to obtain the right amount of angular momentum at take-off. This was shown by Ettema et al. (2016) with regard to the effect of friction force in two imitation jump conditions and confirmed by Lorenzetti et al. (2019). Assuming the transfer of motor skill (James 2012) applies to from imitation jumps to hill jumping, it remains a challenge for the athlete and coach to evaluate imitation jumps regarding expected performance in competition. On the other hand, imitation jumps allow for many repetitions under constant conditions. Thus, indoor imitation training provides a good opportunity for enforcing a particular movement 'strategy' that can be transferred to the hill. It is reasonable to assume that experienced and successful jumpers are more profound in their technical execution compared to their less experienced counterparts and have translated their technique of actual ski jumping into a specific manner of executing imitation jumps, and vice versa. Still, even though coaches and athletes may have a certain understanding about how imitation jumps should be executed, and what aspects of a hill-jump it is that they try to simulate, this has, to our knowledge, never been documented or quantified. Obviously, in this regard, a direct comparison of jumping technique in imitation - and hill jumps is of high interest. As mentioned earlier, the number of repetitions in hill jumping that can be obtained within a reasonable time frame is a great challenge in the sport. This also has scientific ramifications regarding obtaining a reliable estimate of an athlete's technical execution of the ski jump. However, from a practice departure point, it is of similar interest to compare athletes of different performance level on the execution of imitation jumps, because by far most training is spent in and most feedback is retrieved from performing these imitation jumps, not hill jumps (see also Lorenzetti et al. 2019; Pauli et al. 2016).

Thus, our aim was to reveal if any trait in the dynamics and kinematics of imitation ski jumps that relates to the level of performance in competitive ski jumpers could be identified.

While it is difficult to formulate specific hypotheses about how the technical execution is related to performance level, we envisaged that comparing the end state at take-off and the development of motion during push-off towards that end state would enhance understanding of the role of imitations jumping for ski jump performance.

Methods

Eleven male competitive ski jumpers (height 1.76 ± 0.1m, body mass 62.8 ± 7.0 kg, age 20.5 ± 3.0 yrs), all from the same regional team, including two members of the Norwegian national team, volunteered to participate in the study. The jumpers ranged from regional (two junior athletes no ranking, 7 athletes with national ranking from 10^{th} to 64^{th}, competing in national league and international league level 2) to world-class level (competing in the world cup series, i.e., international level 1, world ranking 6^{th} and 13^{th}). Two world-class level jumpers (national team members) were considered to be of a distinctively better level than the rest of the participants. Prior to testing all participants gave written consent to participation. The Norwegian Centre for Research Data approved the study.

Data collection was completed during three consecutive days of testing, just prior to the winter season (early November). The athletes performed imitation jumps on short roller skis from an indoor take-off ramp (6m, sloped 2° downward) and onto a gymnastics mattress. This is a part of ordinary indoor practice for these athletes. They used their personal ski jumping boots on a set of aluminium roller skis, custom built for the occasion of the study. Custom-built force plates with standardized piezoelectric force cells (Kistler 9143B, Kistler Instruments, Winterthur, Switzerland) were attached between roller ski frames and ski bindings. The total weight of this construction exceeded the regular jumping ski system by 1.5 kg.

To obtain an accurate estimate of the technical jumping profile, 15 jumps were performed. Only jumps that were approved by athlete and coach as ‘successful’ (on face value), were considered for further analysis. This led to a minimum of 13 qualified jumps per athlete. Due to technical issues some jumps were excluded for analysis, leading to 8 (one athlete) 10 (two), 11 (one), 13 (six), and 14 (one) repetitions included in the final analysis, which was based on the average profile of these included repetitions.

The athletes were instructed to perform imitation ski jumps in the way they practice these. Ample time was given between jumps to avoid fatigue, both physically and mentally. Data collection lasted 15 s and started shortly after the athlete had indicated he was ready for the exercise. In return, the athlete was signalled that data collection was initiated, which gave him ample time to execute the task which took about 5 s.

A motion capture system (Qualisys, Gothenburg, Sweden) with seven Oqus cameras was used for kinematic data collection. To identify body segments and corresponding joints, seven reflective markers (1cm diameter) were placed unilaterally on the following landmarks: the lateral tip of the acromion (shoulder), the lateral humeral epicondyle (elbow), the ulnar styloid process (wrist), the trochanter major (hip), the lateral femoral epicondyle (knee), and on the surface of the shoe directly over the lateral malleolus (ankle) and the head of the fifth metatarsal (toe). Markers were also placed on the front - and rear end of the force plates to identify force plate position to transfer CoP data from local (plate) to the global (Oqus) coordinate system. On basis of these data, ankle, knee, hip, shoulder and elbow angle and - velocity in the sagittal plane were obtained. The included joint angles are reported. Segment angles (leg, thigh, trunk, arm and forearm) were calculated relative to the horizontal. Increase of these angles were defined as positive (leading to positive velocity). Prior to data collection, the force plates of the skis were calibrated using a regular force plate (Kistler 9286AA, Kistler Instruments, Winterthur, Switzerland), both with static forces and by performing imitation ski jumps using the same roller skis with wheels removed from the force plate. The difference in vertical force was less than 1% and CoP in fore-aft direction differed less than 0.003 m. Vertical force measurements were synchronized with 3D motion capture using the Qualisys software. Sample rate was 200 Hz for all variables.

Before statistical analysis, all jumps were synchronized (time=0) at moment of take-off, identified by the first sample at which perpendicular ground reaction force (F_z) was less than zero. All data were low pass filtered (fourth-order Butterworth, cut-off frequency 10 Hz). CoM was calculated using anthropometric parameters according to de Leva (1996), which were adjusted for boots and skis. The moment arm d was calculated as the CoP-CoM x-difference (positive values indicating CoP behind CoM relative to moving direction). Because CoM and CoP were calculated independently from each other, a small artificial offset of d could be obtained. During a static position over a longer period, this moment arm should be zero on average (by definition). Any offset found over such period must be artefact and subtracted from the original signal. The in-run period that could be considered static was deduced to occur from -2.0 to -1.5 s before take-off: the athletes used about 4-5 s from release to take-off, of which about the first second to obtain the static tucked in-run position, and take-off movement is executed well within 0.5 s, assuring that the -2.0 to -1.5 window was (close to) static. Angular momentum was averaged from the integration of moment (i.e., force × d) over time and summation of angular momentum of the body segments as obtained by the kinematic measurements, with moment of inertia adjusted from de Leva (1996).

A team of the participant's coaches evaluated the jumpers and ranked them according to expected level of performance in an actual hill jump competition. The ranking was meant to mirror their expected performance level at the actual test day, not the upcoming winter season. The three coaches knew all athletes and agreed on the ranking. The athletes were ranked on a scale from 1 to 11, of which 1 was considered the best.

Statistics

The period from -1.5 to 0 s from take-off was analysed statistically. Spearman correlations (rho_i) with performance level of the athletes were calculated for all time traces of interest (i). Corresponding p-values (N=11) were calculated and presented as time traces as well. Thus, for each variable a new rho_i - and p_i - time trace was generated (see Fig. 1). To assess the significance of the entire time trace period of interest (300 samples), binomial statistics were applied. Alpha was conservatively set at 0.01 and the p-value for obtaining the number of significant adjacent data points (which in this case was 9 samples out of 300, 0.04 s) out of 300 was tested according to a binomial distribution with the same alpha.

All time signals depend on each other according to Laws of Mechanics and/or because of overlapping dependency on the measurements. This obviously increases the chance for type II error by multiple testing on the same data. Thus, we were careful with interpreting our findings by considering any significant kinematic and dynamic outcome as being mechanically interdependent, i.e., we regarded any outcome as a specific aspect of one movement execution (Arndt et al. 1995; Denoth et al. 1987; Virmavirta and Komi 1993b).

Results

Figure 2 shows the time traces (mean and SD) for vertical acceleration and for variables showing periods with a significant relationship with performance level. Vertical acceleration profile is shown as one of the fundamental variables but showed no relationship with performance level. The resulting velocity of CoM, however, showed significance towards the end of the take-off. Any variable not displayed in the figure did not have any period with significant correlation. Below, a brief elucidation of how the variables mechanically relate to each other is given.

At the onset of the jump, a backward (positive) angular momentum was generated by a positive moment, before this was turned into a considerable forward momentum (by negative moment) while moving into the typical take-off position. Moment and resulting angular momentum were related to performance level only during the middle of push-off: the better athletes generated less backward momentum at this stage. No relationship with performance level was found at the later stages of the take-off action. The dynamics of this interplay between generating linear momentum by force and angular momentum by moment is best shown in the development of the moment arm. Moment arm showed the clearest relationship before and during the early period of push-off: the best athletes tended to have the smallest moment arm. Note that the moment arm initially is slightly negative, i.e., CoP is just in front of CoM.

Of the kinematic data, only thigh angle showed clear and long-lasting significant periods during push-off. The better athlete had a larger thigh angle, i.e., the thigh had rotated forward to lesser extent. Forearm and elbow angular velocity were significant during a short period up to about halfway through the jumping action in a negative manner, i.e., the best athletes showed the lowest velocity.

When considering the late push-off period, only thigh angle and CoM velocity showed significance.

Discussion

The aim of this study was to identify particular traits of imitations jumps that relate to ski jumping performance level. Of the analysed variables, moment arm (before and early during push-off), angular momentum (early during push-off), vertical velocity (late in push-off), and thigh angle (during push-off) appeared to be most discriminative for the current group of athletes. Below follows a deduction on how these findings may relate to actual performance in hill jumping. In this respect, while we seek for mechanical similarities ('traits') between imitation – and hill jumps, it should be noted that our results are no foundation for a direct comparison of the mechanics under these two conditions.

It is important to note that at initiation of the push-off action, no relationship of starting pose with performance level was found. This is in contradiction with findings on junior athletes in hill jumping (Zanevskyy and Banakh 2010). This may be because all athletes were trained under the same technique philosophy including this initial pose, and our data concern imitation jumps, not hill jumps. Force (and acceleration) profile of the push-off did not discriminate better from poorer ski jumpers, which is in contradiction with older findings in ski jumping in the hill (Virmavirta and Komi 1993b). Yet, the integrated outcome, i.e., vertical velocity is highest for the best jumpers, which does confirm that same study (Virmavirta and Komi 1993b). Comparison with much older literature should be done with caution because of the development of the sport (Janura et al. 2010). However, that after a period of almost 30 years the relevance of vertical take-off velocity is once more documented (see also Pauli et al.

2016) indicates the importance of this factor despite that it may compromise quickly obtaining an aerodynamic position. The disappearance of the significance of this velocity factor at the very end of push-off may not be relevant in actual hill jumping because the athlete will most likely have left the take-off table earlier (Fig.2, also see Virmavirta et al. 2001). This is also indicated by the relatively large knee angle at take-off during the imitation jumps (142 ± 5°) compared to what is observed in practice in hill jumping, i.e., ~130° (unpublished and deduced from Virmavirta et al. 2009). In a slightly different manner do moment and development of angular momentum show interesting relationships with performance level. The angular momentum development depends on performance level during the mid-phase of the push-off action, which is nullified during the remainder. Thus, even though athletes may have different angular momentum at lift-off, the amount is not related to performance level. These findings can be assimilated as follows: during imitation jumps, the better athletes seem to have their CoM and CoP more closely aligned in the last second before the push-off action is initiated. Thereby, the poorer jumpers produce more backward rotation that needs to be reversed in the later part of push-off. It may be speculated that the poorer athletes minimize this challenge by producing somewhat (non-significant) lower push-off force that leads to a slightly lower (significant) vertical velocity towards take-off. The development of angular momentum (first backward rotation that is reversed in the last phase of push-off) is in agreement with imitation jumps in Ettema et al. (2016). Still, the CoM-CoP alignment during the first part of push-off differed between these studies. This may be due to the differences in conditions as was the case between jumping from a rolling platform and fixed-floor imitation jumps (Ettema et al. 2016).

The stronger movement of the upper extremity at the start of push-off should not be judged on face value. The current group of ski jumpers have been trained under the philosophy that the arm should be kept still as a departure point but can be used as a (small) corrective means for maintaining balance. Thus, our findings may be indicative for the challenge that the poorer athletes have maintaining (or obtaining) optimal kinematics and balance. Arm movement is often seen in the best athletes during push-off in ski jumping, but it is not free of limitations because of its aerodynamic effect during push-off (Yamamoto et al. 2016) and the aerodynamic position that must be established in early fight. Still, the relationship of arm movement with performance level was only revealed in the velocity during a short period early in the push-off, not in the obtained arm position. Thus, if this technical aspect of the jump execution is making a difference in the hill is unclear.

Apart from thigh position (see below) and possibly vertical velocity, none of the examined variables at the time of take-off showed any relationship with performance level. Thus, any difference between better and poorer athletes is found more in how the take-off state is obtained rather than what that state is, a position also suggested by Lorenzetti et al. (2019). This triggers the question about the relevance of the imitation jumps for real ski jumping. It should be noted that we have no physical indication that the better jumper executed the imitation jumps better than the poorer ones. In fact, even though coaches and athletes have a clear notion of what contains a well-executed imitation jump, that the better athletes perform imitation jumps better is rather the assumption that this study relies on with regard to the interpretation of the findings. In this regard, the inherent challenge in ski jumping practice and -research is determining what is the optimal compromise between generating linear and angular momentum. Yet, since the final state at take-off of the jumps is not related to performance, we suggest that the essence may lie in the transferability to real jumping of the applied technique. Our study cannot ascertain any role of this transferability. However, the compatibility between imitation jumps and hill jumps (Lorenzetti et al. 2019) supports such notion. For example, the small CoM–CoP misalignment and the related small but still higher backward rotation that poorer athletes generate may easily be handled in the imitation condition but may lead to considerable challenges in the hill. One important limitation is the earlier take-off in hill jumping compared to the imitation jumps, particularly because of ~50-70N aerodynamic lift (Virmavirta et al. 2001), and even reduced gravitation effect (10-15N) coming down on a negatively sloped take-off table may contribute to some extent. The last period of the push-off action may not be available to the athlete in the hill (see Fig. 2). This implies that the athlete’s opportunity to reverse a backward rotation is considerably less than in imitation jumps. In the hill, this challenge may be larger because of the aerodynamic pitching effect (Yamamoto et al. 2016).

The role of body position at take-off for jumping performance is often regarded as a compromise between creating linear momentum, i.e., vertical velocity, and aerodynamic position (through rotation) (e.g., Arndt et al. 1995; Virmavirta and Komi 1993a; Virmavirta and Komi 1993b). Interestingly, the only body position variable that appeared to be related to performance level during a large (particularly later) period of the push-off, was thigh angle: less forward rotation was associated with good performance. Of course, the differences in thigh angle must be reflected in differences in other segment or joint angles . Apparently, in the examined imitations jumps, various small variations in local kinematics of this coordinated movement centre on the positioning of the thigh. Our findings are opposite to those from the Czech research group (Janura et al. 2011a; Janura et al. 2011b), who found that, in the hill, a more progressive thigh angle at take-off is associated with better performance, which they argued would lead to a better aerodynamic position. It is difficult to deduce what may have caused this discrepancy and how this angle relates to dynamics, but it can be suggested that the thigh position is essential for positioning CoM optimally above the foot while maintaining good joint configuration for power generation. Thereby, the condition to generate linear momentum may be improved, still maintaining an aerodynamic position, optimizing lift/drag ratio, minimizing backward pitching (e.g., Yamamoto et al. 2016), while obtaining the required position for flight . Note that in our imitation jumps the differences in thigh angle were not associated with differences in, the aerodynamically important, trunk angle. Clearly, this aspect, particularly the link between imitation and hill jumps, needs further elaboration (e.g., Lorenzetti et al. 2019).

In summary, the current findings suggest that imitation jumps deal with technical execution that is transferrable to the actual hill, rather than reaching a final optimal body configuration state at take-off. Still, the orientation of the thigh during push-off and at take-off may be the most important isolated kinematic variable that is associated with performance, a notion to be verified by future research.

Methodological considerations

The 11 athletes that participated in the current study were trained under the same ‘philosophy’ for technique. This was essential to the study, which aimed at investigating performance level rather than different styles or jumping techniques. Thus, while we believe that the findings regarding the principles of (imitation) ski jumping are of relevance, it is difficult to ascertain the generalizability of the specific findings (e.g., on thigh position).

The calculations of moment arm and angular momentum relied on accurate estimation of CoM. Because CoM calculations depended partially on literature data (de Leva 1996), systematic errors may have been introduced (Fritz et al. 2019). The impact of this for moment arm and related variables was accounted for by CoM–CoP alignment corrections (see Methods). Still, this procedure does not warrant against any systematic offset of CoM and moment arm. If any such systematic offset was related to the athletes' anthropometrics, this could have affected the outcome of this study. We examined this possibility by running the same analysis procedure against order of body mass, height, and BMI. Almost all of the significant correlations of the time traces in the original analysis (against order of performance level) disappeared. Furthermore, the two calculation methods for angular momentum (one based on kinematic data only) that we averaged for the analysis showed the same time trace shape, be it that the amplitude was different. This strengthens the notion that the relationship of development of moment arm and angular momentum with performance level is genuine. Still, caution should be taken regarding the exact values found in this study.

Ski jumping performance was not tested by actually monitoring the kinetics of hill ski jumping. Apart from the obvious reason of the cumbersome challenge to do so accurately, performance in the hill depends on more factors than only the take-off action. It is questionable if a limited number of jumps in a brief period under naturally varying wind conditions would have given a better indication of the performance level of the athletes than the approach used in this study. Of course, such measurements are of enormous value for the direct kinetic comparison of imitation and hill jumps (e.g., Lorenzetti et al. 2019).

We interpreted our findings by focusing on significant correlations from a conservative standpoint to minimise the type I error, i.e. false positives. Still, our significant findings are thereby not proven to be beyond trivial. Nonetheless, the periods of significance had an effect size $r^2 > 0.56$, which is regarded as large. Still, we believe that this issue can hardly be addressed by applying different statistical approaches, because we do not know how large a meaningful difference in, for example, moment arm before jump onset is. Thus, this study is explorative in nature, posing, not testing, relevant hypotheses.

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Figure captions:

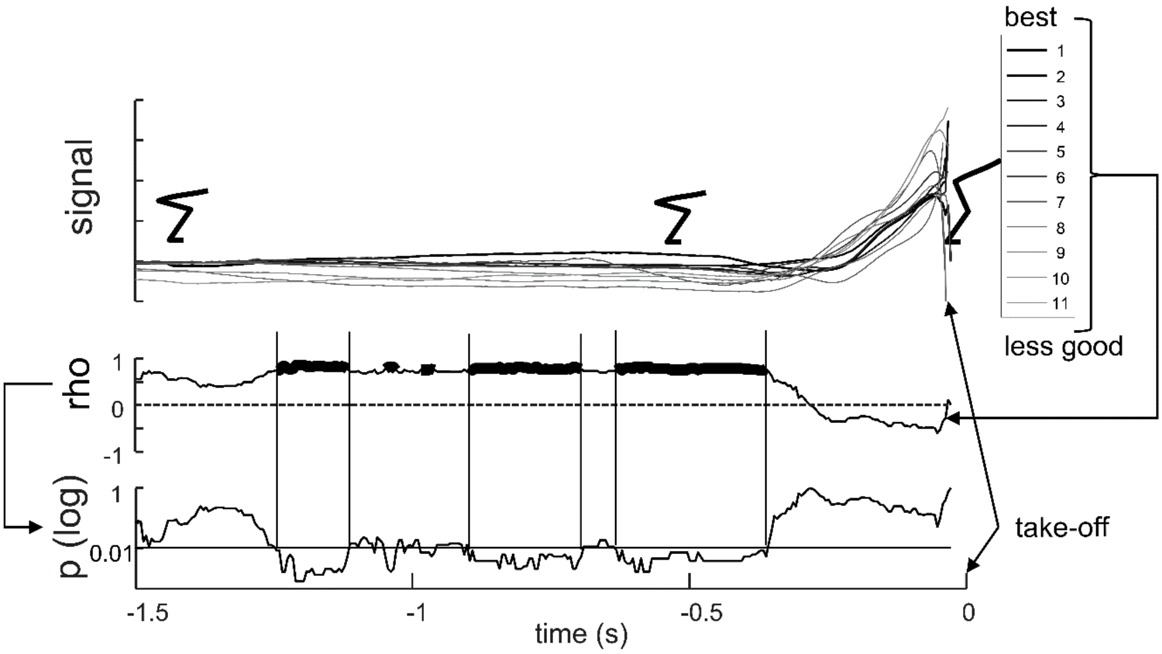

Fig. 1: Generation of Spearman correlation (rhoi) time traces. The signal (time trace in top diagram) of interest (here moment arm d) is correlated at each sample with order of performance level, leading to rhoi trace (middle diagram) and associated p-value trace (bottom diagram). Significant periods lasting at least 0.04 s are indicated by fat part of the traces combined with vertical indicators (two shorter periods at about -1 s are discarded through this process).

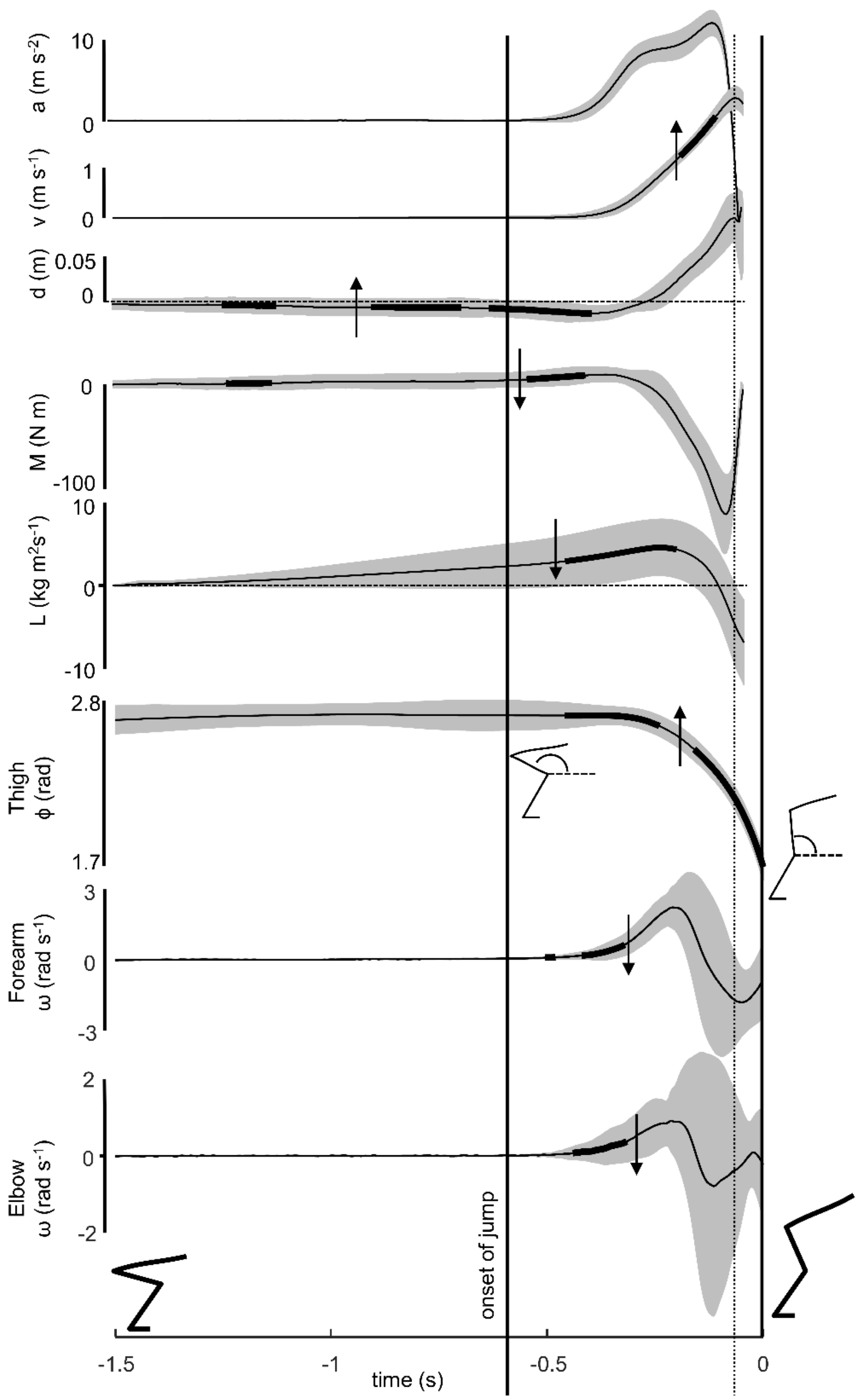

Fig. 2: Dynamic and kinematic time traces (mean of 11 athletes, std indicated by grey areas). Significant periods are indicated by fat lines. Approximate onset of push-off action and take-off (t=0) are indicated. Dotted vertical line indicates the likely approximate take-off time in ski jumping in the hill (Virmavirta et al. 2001). Small vertical arrows indicate the direction of significant correlations, the arrows point into the value direction of the best athletes.

a: vertical acceleration; v: vertical velocity; d: moment arm of vertical force; M: moment; L: angular moment.