Different solutions in generation of angular momentum during imitation jump take-offs among diverse level ski jumpers

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Abstract

Introduction: During the push-off motion in ski jumping, the athlete strives to generate both a high vertical velocity and a correct angular momentum. The latter is important as it brings the athlete into the flight position. The ground reaction force (GRF) acts with a moment arm (*d*) upon the ski jumpers centre of mass (CoM). The interplay between the *d* and the GRF is responsible for creating the angular moment from which the necessary angular momentum of the ski jump transpires. This study aimed to describe how ski jumpers generate the angular momentum in indoor imitation ski jumps, and how different kinetic parameters of the generation are related to skill. **Methods:** Eleven male ski jumpers performed 13-15 consecutive jumps from an indoor take-off ramp. Kinematics and the GRF-vector was recorded. CoM was calculated with base in kinematic data, using the individual body-segments length and mass. The athletes were ranked according to expected level of performance at the actual test day. To relate the analysed variables to performance level, Spearman's rank correlation analysis was used. Rho were plotted as a function of time in order to look at trends throughout the push-off phase. **Results:** The angular momentum was generated in the later part of push-off motion. The late development is linked to the ski jumper's late alteration of *d*. Significant correlations to performance were found in both vertical force production, the length of *d*, as well as in the rate of change in *d*. Total angular momentum showed no correlation to performance either during the push-off nor at the actual take-off (first time sample with GRF≤0). The correlations between performance and vertical force were found during a brief interval of the early push-off, when the better jumper tended to exert the greater force. Correlation trends in *d* showed wider intervals of significant correlations: The better jumper tended to enter the transition phase between the in-run and the push-off with a *d* closer to zero in comparison to the lower ranked athletes, who typically entered this phase with small negative values of *d*. Also, the better jumpers tended to both delay the onset of change in *d*, and have the lesser rate of change in *d* during a large part of the push-off. Eventually, this means the better jumper both entered and left the push-off with values of *d* closer fixated around zero. **Discussion:** It seems as the athlete's different solutions in generation of angular momentum might be a result of the interplay between force production and orientation of the GRF-vector; trends in data suggests the poorer athletes to make up for a slight lack of force by having the longer *d* throughout the push-off. During the in-run athletes seem to control *d* in order to enter the push-off in a specific state.

Keywords: *Ski jumping; kinetics; angular momentum; take-off;*

Sammendrag

Introduksjon: I skihoppets satsfase ønsker skihopperen å skape en høy vertikal utgangsfart og et samtidig korrekt rotasjonsmomentum. Rotasjonsmomentumet er avgjørende for å få hopperen til den korrekt stillingen i svevfasen. Motkraften fra bakken (GRF) virker med en momentarm (*d*) på skihopperens massesenter (CoM). Samspillet mellom *d* og GRF skaper et rotasjonsmoment, fra hvis tidligere nevnte rotasjonsmomentum forløper fra. Dette studiet ønsket å beskrive hvordan skihoppere genererer rotasjonsmomentumet i imitasjonshopp, samt hvordan ulike kinetiske parametere av denne genereringen korrelerer med skihopprestasjon. **Metode:** Elleve mannlige skihoppere utførte 13-15 påfølgende hopp fra en innendørs rampe. Kinematikk og GRF (med tilhørende trykksentrum) ble målt. Med base i kinematiske data av kroppssegmenter, ble CoM kalkulert. For å relatere ulike kinetiske parametere tilknyttet generasjonen av rotasjonsmomentumet til prestasjon i utendørs skihopp, ble Spearman's rangkorrelasjon benyttet. Rho ble plottet over tid for å se på trender gjennom satsfasen av skihoppet. **Resultater:** Dette studiet viser at rotasjonsmomentumet som skapes i skihoppets satsfase, typisk oppstår i siste del av satsfasen. Den bakenforliggende grunnen til dette er hopperens sene utvikling av *d*. Signifikante korrelasjoner til prestasjon ble funnet både i produksjon av vertikalkraft, endring av *d* og raten av endring i *d*. Totalt rotasjonsmomentum viste ingen korrelasjon til prestasjon under satsfasen. Produksjon av vertikalkraft viste små korrelasjoner til prestasjon; kun i et kort tidsintervall i begynnelsen av satsfasen produserte de bedre hopperne signifikant mer kraft enn de lavere rangerte. Når det kom til *d*, forekom større perioder med signifikant korrelasjon mot ferdighet. De bedre utøverne viste en tendens til å ha verdier av *d* nærmere null i overgangsfasen mellom tilløp og sats i forhold til de lavere rangerte, som typisk i denne fasen hadde små, negative verdier av *d*. De bedre hopperne hadde også en tendens til å forsinke starten av endring i *d*, samt ha en mindre rate av endring i deler av satsfasen. **Diskusjon:** Det ser ut til at utøvernes ulike måter å generere rotasjonsmomentumet på, er et resultat av samspillet mellom vertikalkraft og *d*; trender i datasettet peker mot at eksempelvis de dårligst rangerte hopperne øker lengden på *d* for å kompensere for en noe lavere kraft. I tilløpet virker utøverne å kontinuerlig tilpasse sin positur, sannsynligvis med det mål om å entre satsfasen i en spesiell stilling.

Nøkkelord: *Skihopp; rotasjonsmomentum; satsfase; kinetikk;*

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1. Introduction

One phase of the ski jump is considered dependent upon the previous (1, 2). Consequently, actions made during the push-off phase determines the initial conditions for the following flight phase (1, 3, 4). The push-off phase is considered the most crucial phase of the entire ski jump (1, 3, 5-7).

Field of best practice widely implements indoor imitation jumps as a training method to practice the push-off motion in ski jumping. For ski jumpers, this type of exercise has the benefit of being time effective, weather independent and with the possibility of immediate and accurate feedback. The imitation jump differs from the actual hill jump to a point where several boundary conditions are unlike to a motion-defining level (8-10). Mostly, this is due to the absence of lift force during the push-off motion of the imitation jump (8, 9). Even so, the indoor imitation jump is a well-known exercise for ski jumpers upon which several, recent studies have been conducted (5, 11).

The push-off motion relies on an optimization of several inter-connecting parameters (1, 12): The athlete strives to generate a high vertical velocity and, simultaneously, create a forward rotating angular momentum (1). Vertical velocity at take-off has been the topic of several studies in the past and is suggested to play a large role in ski jump performance, with the higher velocity being related to the better performance (1, 3, 13). In generation of maximal vertical velocity, one must aim to maximize the vertical component of the ground reaction force (GRF). However, in generation of angular momentum, one must aim to generate only the correct amount of rotational momentum, not to maximize it. A maximization of the angular momentum would simply lead to the ski jumper somersaulting. The angular momentum is thus of high importance to the ski jumper when it comes to reaching an optimal flight position.

In order to create the necessary forward rotating angular momentum of the ski jump, the athlete must first create the moment from which the angular momentum progresses. The outcome of this moment has to have certain characteristics, if the jumper is to end up in a viable flight position. It has to both nullify the backward rotating angular momentum caused by the exit of the curved part of the in-run (14), and, in addition, create a small forward rotating momentum. The latter must be of a degree that is, in the early flight phase, nullified by the oncoming air-stream (15). This would result in the ski jumper stabilizing in the flight position.

As one cannot generate shear forces for propulsion in ski jumping (5), the line of the GRF runs perpendicular to the take-off table. The origin of this line is the athletes centre of pressure (CoP). Consequently, a moment arm between CoP and the athletes centre of mass (CoM) is created in the sagittal plane. If the GRF is set for producing the maximal vertical velocity obtainable, this moment arm (*d*) then defines the amount of angular momentum being generated. It does so by being the only mechanical parameter that can be changed in order to obtain the correct angular momentum. Likewise, if all variables of the push-off except the GRF were static, a rise in this force would induce a greater angular momentum, should the length of *d* not be zero. To conclude, an elevation of the GRF would result in a shorter *d* needed to achieve a certain angular momentum, and a longer *d* would need less force to induce the same angular momentum. Thus, the ski jumper must carefully control the length of *d* in relationship to his or hers force production during the push-off phase. A visual presentation of the above-mentioned terms can be found in Appendix A.

The interplay between these two variables implies that different level jumpers might generate the angular momentum in different ways. It is appropriate to suggest since former studies, as earlier mentioned, have proposed a relationship between vertical velocity at take-off and performance (1, 3, 13). By altering one of the two variables and still produce a similar angular momentum, this potential change in angular momentum must be nullified by additional altering of the other. That is, of course, if the different level athletes in fact hold a similar angular momentum when leaving the take-off table. No previous studies have investigated the mechanical solutions in the generation of the angular momentum in ski jumping. Consequently, little is known about how the athletes generate their angular momentum. A better understanding of kinetic parameters of the imitation jump could enhance regular practice and be of relevance when ski jumpers seek feedback on their performance during indoor training. A closer investigation of the generation of angular momentum could also point out directions for upcoming studies on ski jumping, as it enlightens a subject yet to be closely examined. The aim of this study was to describe how ski jumpers generate the angular momentum in indoor ski jumping, and how different kinetic parameters of the generation relate to skill.

2. Methods

2.1 Participants

Eleven male ski jumpers (height 1.76 ± 0.1m, body mass 62.8 ± 7.0 kg), volunteered to participate in the study. Prior to testing all subjects gave written consent to participation. The Norwegian Centre for Research Data approved the study.

2.2 Protocol

The data collection was completed through three continuous days of testing, in early November 2016. The athletes performed 13-15 consecutive jumps, each from an indoor take-off ramp (6m, sloped 2° downward) and onto a substantially padded gym mattress. Ordinary indoor practice among the athletes typically tend to be executed in such a manner. During the test procedure, the athletes used both roller skis and ski boots. They used their personal ski jumping boots, whereas the set of roller skis were custom built in the occasion of the study. The roller skis were made up by an aluminium frame holding the same width as ordinary ski jumping skis. Wheels and regular bindings for ski jumping were attached to the outside of the frame of the skis. Custom built force plates (described under "2.3 Measurements") were installed inside the frame. The equipment was meant to mimic that of outdoor practice and negate the use of shear forces for propulsion. One custom roller ski held an additional weight of approximately 760 grams when compared to one ordinary ski for outdoor use. The roller skis were not tested by any of the included ski jumpers prior to the data collection.

2.3 Measurements

At the test location, a seven-camera Oqus (Qualisys, Gothenburg, Sweden) 3D motion capturing system was set up to record kinematics of the indoor ski jump. 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, the lateral humeral epicondyle, the ulnar styloid process, the trochanter major, the lateral femoral epicondyle, and, on the surface of the shoe, directly over the lateral malleolus and the head of the fifth metatarsal. Some markers were also placed on the forth end and back end of the force plates in the skis to transfer force plate data to the global coordinate system of the motion capture data. In addition, two markers were placed on the in-run ramp, to locate the ski jumpers position.

Dynamic parameters were measured by custom built force plates with standardized piezoelectric force cells (Kistler 9143B, Kistler Instruments, Winterthur, Switzerland) located inside the earlier mentioned skis. Prior to data collection, the force plates of the skis were compared to a regular factory-made force plate (Kistler 9286AA, Kistler Instruments, Winterthur, Switzerland), showing a difference in measurement of <1% regarding force, and <0.003m in CoP. The force cells were calibrated prior to each jump. A single data recording normally lasted for approximately 10 seconds. Both systems of motion capture and force measurements were set to operate at a sampling rate of 200 Hz.

2.4 Ski jump performance ability

A team of the participant's coaches was assigned the task of evaluating the jumpers, and rank 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 athletes were ranked on a scale from 1 to 11, of which 1 was considered the best. The jumpers ranged from regional to world-class level. Two jumpers were considered to be of a distinctively better level than the rest of the participants.

2.5 Analysis

Negative angular momentum is defined as forward rotation of the body. Positive values of *d* are associated with the GRF-vector acting behind the athletes CoM, creating a (negative) forward rotating momentum.

All data were synchronized and aligned using the exact take-off time (the first sample with the GRF$\leq$0) as a reference sample. The time period included in the analysis starts at 2 seconds before the take-off. Kinematic data were low-pass filtered (2nd order zero-lag Butterworth, cut-off 10 Hz). Whole body CoM was calculated by using the anthropometric data according to de Leva (16), using individual segments length with basis in recorded kinematic data and individual body mass. CoP was determined using the force plates mentioned under "3.3 Measurements". Levels of angular momentum is presented as whole-body angular momentum. Two analyses of *d* were conducted, using both original data and data corrected for a possible offset. Rate of change in *d* and rate of force development (RFD) was implemented in the study to describe the development of the variables in more detail. Force data used for correlation analysis were normalized for the individual athlete's body weight. Both force data normalization and adjustments in *d* were done using the initial 0.2 seconds of the time trace as a reference value.

All data processing was computed using purpose-written code in a commercial software package (MATLAB 9.0, The MathWorks Inc., Natick, MA, The United States, 2016) for Windows 10 (Microsoft Co., Albuquerque, NM, The United States, 2016). Spearman's rank correlation analysis was used to relate the analysed variables to performance level. Level of statistical significance was set to $p \leq 0.05$.

Data are presented in time traces. This gives the opportunity to look at fluctuations in parameters throughout the push-off motion. This is of importance as the goal in this study is not necessarily to describe the angular momentum as an end outcome, but rather the mechanical solution to reach it. Correlation data presented in time traces were computed using the mean values of each respective jumper's repetitions as basis for the analysis.

3. Results

3.1 Total angular momentum

Time traces of total angular momentum is presented in figure 1a, its correlation to performance over time in figure 1b. A scatter plot of total angular moment at take-off as a function of performance, is presented in Appendix B3.

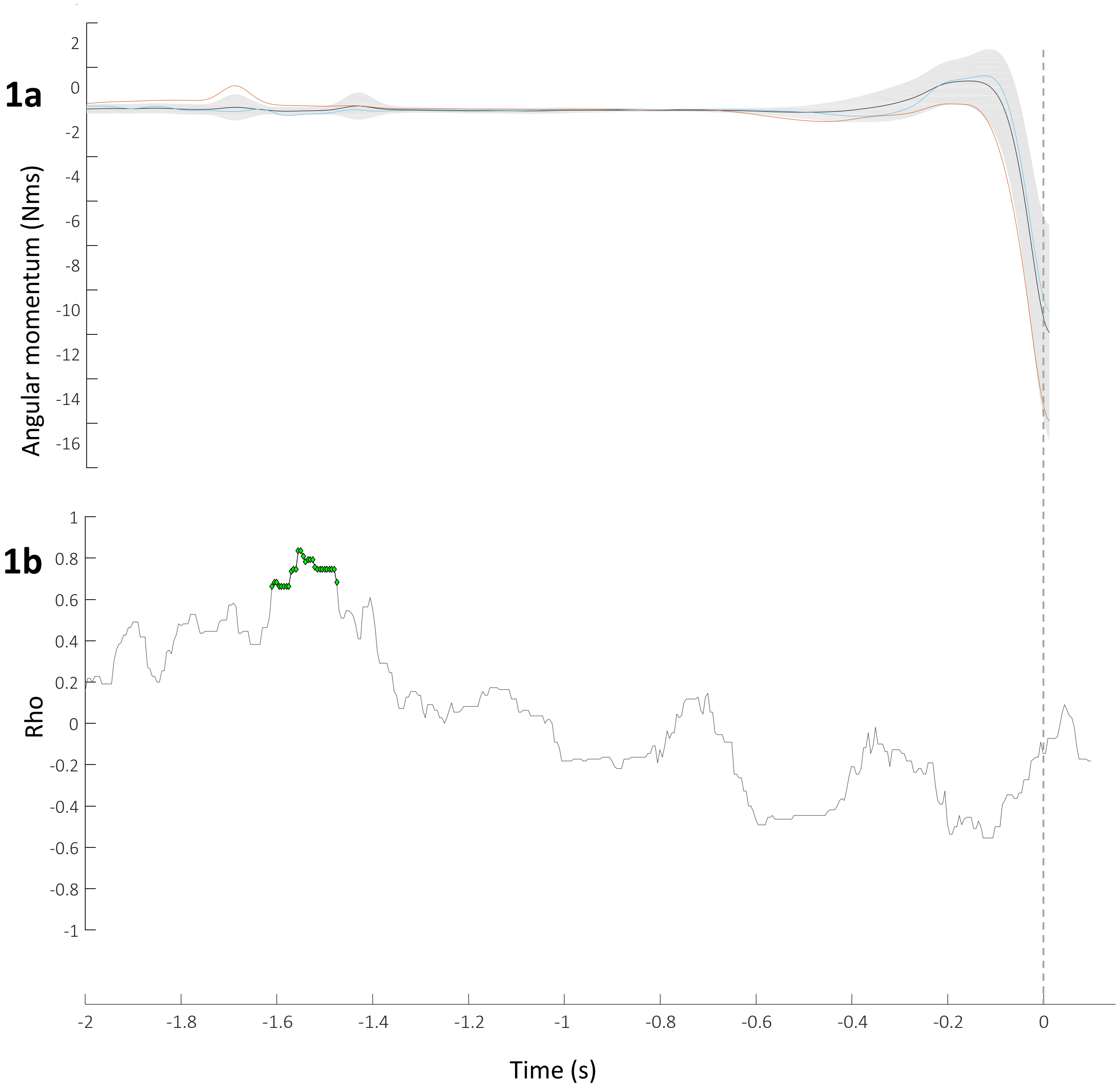


Figure 1: *Total angular momentum at given points in time (a), with corresponding correlations to performance (b). All lines in plot (a) indicate mean total angular momentum: Black line for all jumpers, blue line for the two best ranked jumpers, red line for the two lowest ranked jumpers. Shaded area indicates standard deviations of all jumpers. Bolded part of correlation plot represents p-values of <0.05. Time=0 represents take-off. Grey stippled vertical line represents Time=0.*

The average jumper tended to create a slightly positive, backward rotating momentum during the onset and early phase of the push-off. However, at approximately 0.175s before take-off, a sudden change in angular momentum occurred; it shifted and became increasingly more negative throughout the push-off. This change is associated with the athlete creating the forward rotating momentum necessary to reach the flight position. There was no significant correlation between angular momentum and performance either during nor in the closest proximity to the push-off. On the contrary, an interval ranging from 1.6s-1.45s before take-off (first sample with $GRF \leq 0$) showed a positive, significant correlation to performance. This implies that, during this period, the better jumpers tended to have the more negative rotational momentum or, as defined earlier, a momentum more associated with forward rotation.

3.2 Vertical force production

Unadjusted time traces of vertical force are presented in figure 2a, body-weight normalized vertical force as time traces in figure 2b. The body-weight adjusted force data's correlation to performance over time is shown in figure 2c. A scatter plot of body-weight normalized peak force as a function of performance is presented in Appendix B1.

Fluctuations in vertical force during the in-run were small and did not correlate significantly to performance. The regular push-off motion started at approximately 0.4s before the actual take-off. The jumpers typically produced peak vertical forces at approximately 0.07s-0.05s before take-off. Correlation analysis showed a minor continuous interval of significant correlations between body-weight adjusted force production and rank, in the early phase of the push-off. This time period ranged from 0.235-0.2s before the actual take-off, and held negative correlations. This eventually proposes that the better jumper tended to produce the higher force in this phase of the push-off. Slightly negative, though non-significant, correlations are present during a substantial part of the push-off. No significant correlation between peak normalized force and performance was found.

RFD is presented in figure 3a. It's correlation to performance is presented in 3b. The mean RFD among all athletes showed, as expected, an increase at onset of push-off. Peak RFD occurred at approximately 0.3-0.28s before take-off. Correlation between performance and RFD showed a single significant correlation during the push-off phase; at approximately 0.34s before take-off.

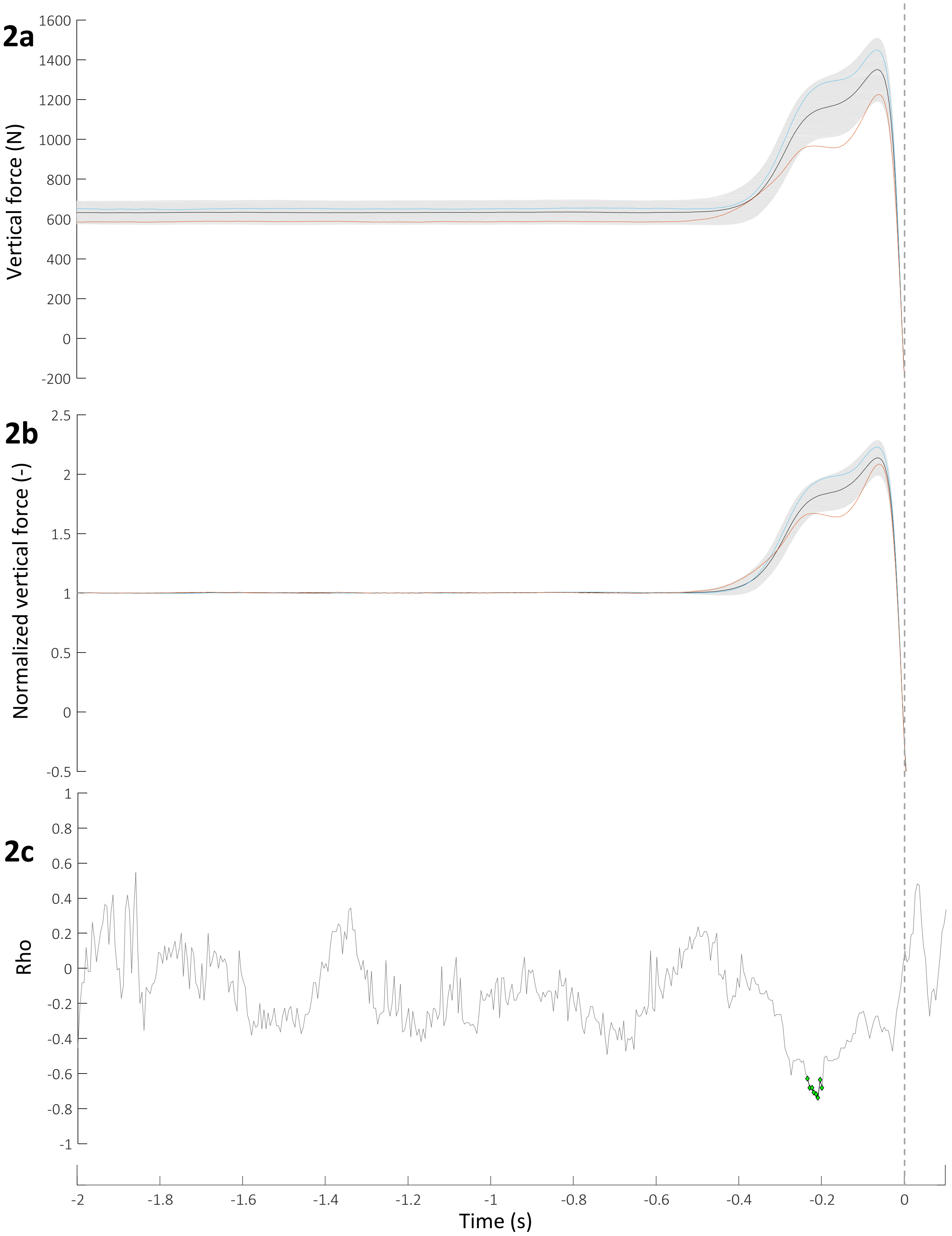


Figure 2.: *Vertical force at given points in time (a), normalized vertical force at given points in time (b) with the latter's corresponding correlations to performance (c). All lines in plot (a) and (b) indicate mean vertical force: Black line for all jumpers, blue line for the two best ranked jumpers, red line for the two lowest ranked jumpers. Shaded area indicates standard deviations of all jumpers. Time=0 represents take-off. Grey stippled vertical line represents Time=0. Bolded part of correlation plot represents p-values of <0.05.*

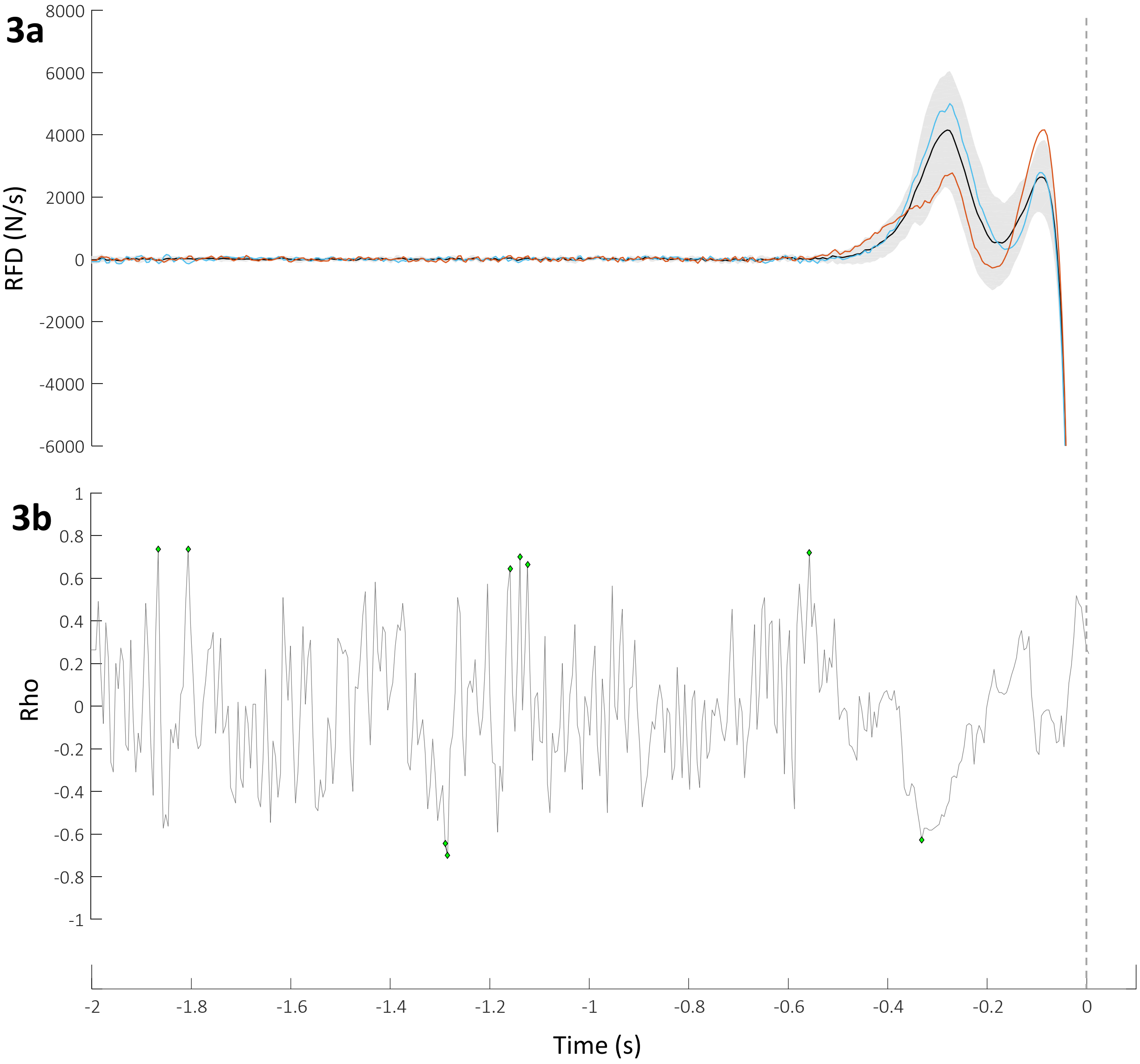


Figure 3.: *Rate of force development (a) with correlations to performance at corresponding points in time (b). In (a), black line represents mean of all jumpers, blue line mean of the two best ranked jumpers and red line mean of the two lowest ranked jumpers. Shaded area indicates standard deviations for all jumpers. Time=0 represents take-off. Grey stippled vertical line represents Time=0. Bolded parts of correlation plot (b), represents p-values of <0.05.*

3.3 The moment arm CoP-CoM (d)

Time traces of *d* is shown in figure 4a. The correlation between *d* and performance is presented in figure 4b and 4c, of which the latter shows correlations of data adjusted for a possible offset. The adjustment is based on the notion that the athletes, at time onset (-2s), holds a static position and thus have no rotation. The offset-adjustment is described in more detail under "4. Discussion". A scatter plot located in Appendix B2 shows *d* as a function of performance at 0.025s before take-off.

During the in-run, small fluctuations are seen in *d*. In push-off phase, *d* is subject to a sudden alteration; the individual athletes GRF-vector runs increasingly more posterior to the respective athletes CoM.

The differences in *d* during the in-run were small in comparison to those of the push-off, but, nevertheless, several significant correlations were found during the in-run phase. As an example, the single strongest correlation of the study occurred at 1.73s before take-off, as a correlation between unadjusted data and performance (rho=0.9091, p<0.001). The only significant correlations mutually apparent in both the adjusted and non-adjusted analysis, are strong negative correlations in an interval just prior to the push-off phase (at approximately 0.95-0.75s before take-off). In this period, the better ranked athletes tended to have the more positive values of *d* when compared to those of lower rank. After closer inspection of data, it appears that the better ranked athletes have values of *d* closer to zero, whereas the lower ranked athletes have small negative values of *d*. This would eventually mean the better athlete’s GRF-vectors tended to run closer to their CoM. In the offset-adjusted analysis, this sequence of significant correlations occurs not only prior to push-off, but extends into the earlier phase of the push-off motion.

During the push-off, a shift in trend occurred. In both analyses, the correlation coefficient altered to become positive during a considerable part of the push-off motion, eventually peaking in significant values. On time points of significant correlations, this implies that the lower ranked athletes tended to have greater positive values of *d*, in comparison to their better ranked counterparts.

In conclusion, the lower ranked jumpers tended to advance from having the more negative *d* to the more positive *d*, throughout the push-off phase. As an illustration of this phenomena, it is possible to see the *d* of the two lowest ranked jumpers (red line) start off with a more negative value and surpass the *d* of the two best ranked jumpers (blue line) to become more positive, in figure 4a.

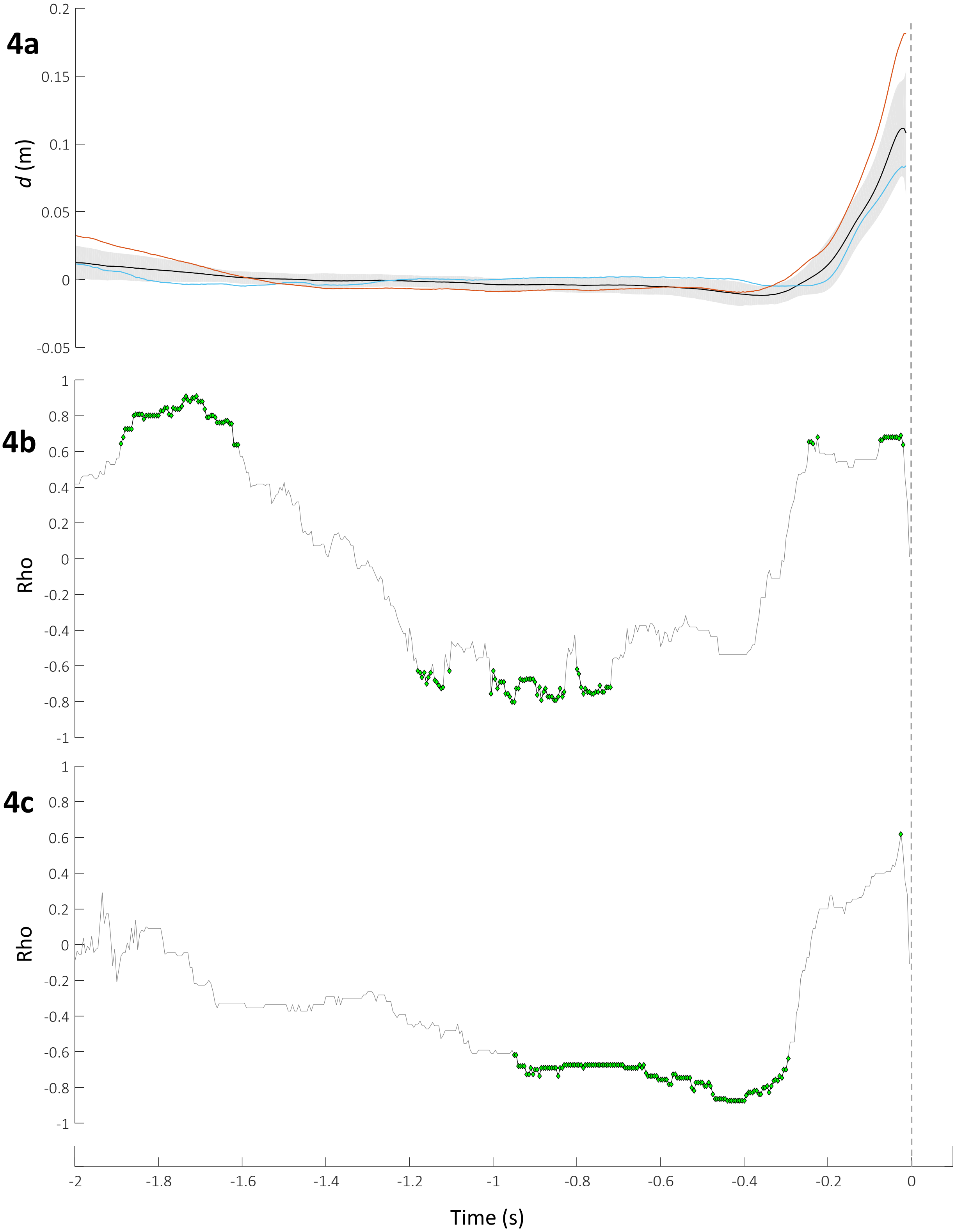


Figure 4.: *Length of the d in meter (a). All lines in plot (a) indicate mean values in d: Black line for all jumpers, blue line for the two best ranked jumpers, red line for the two lowest ranked jumpers. Shaded area indicates standard deviations of all jumpers. The unadjusted data's correlation to performance is presented in figure (b), whereas that adjusted for a possible offset is presented in (c). Time=0 represents take-off. Grey stippled vertical line represents Time=0. Bolded part of correlation plots represents p-values of <0.05.*

The rate of change in *d*, as well as its correlation to performance, is presented in figure 5. Both continuous intervals and single time points were found to hold significant correlations both during in-run and push-off. Within the push-off, significant correlations are typically seen as single peak values. At time 0.07s-0.04s before take-off, a continuous sequence of significant values occurred. During this period, the better ranked ski jumpers tended to have the lesser rate of change in *d.* Further on, in the early phase of the push-off, the correlation analysis partly suggests a trend among the jumpers; that the better athletes have a later onset in change of *d*.

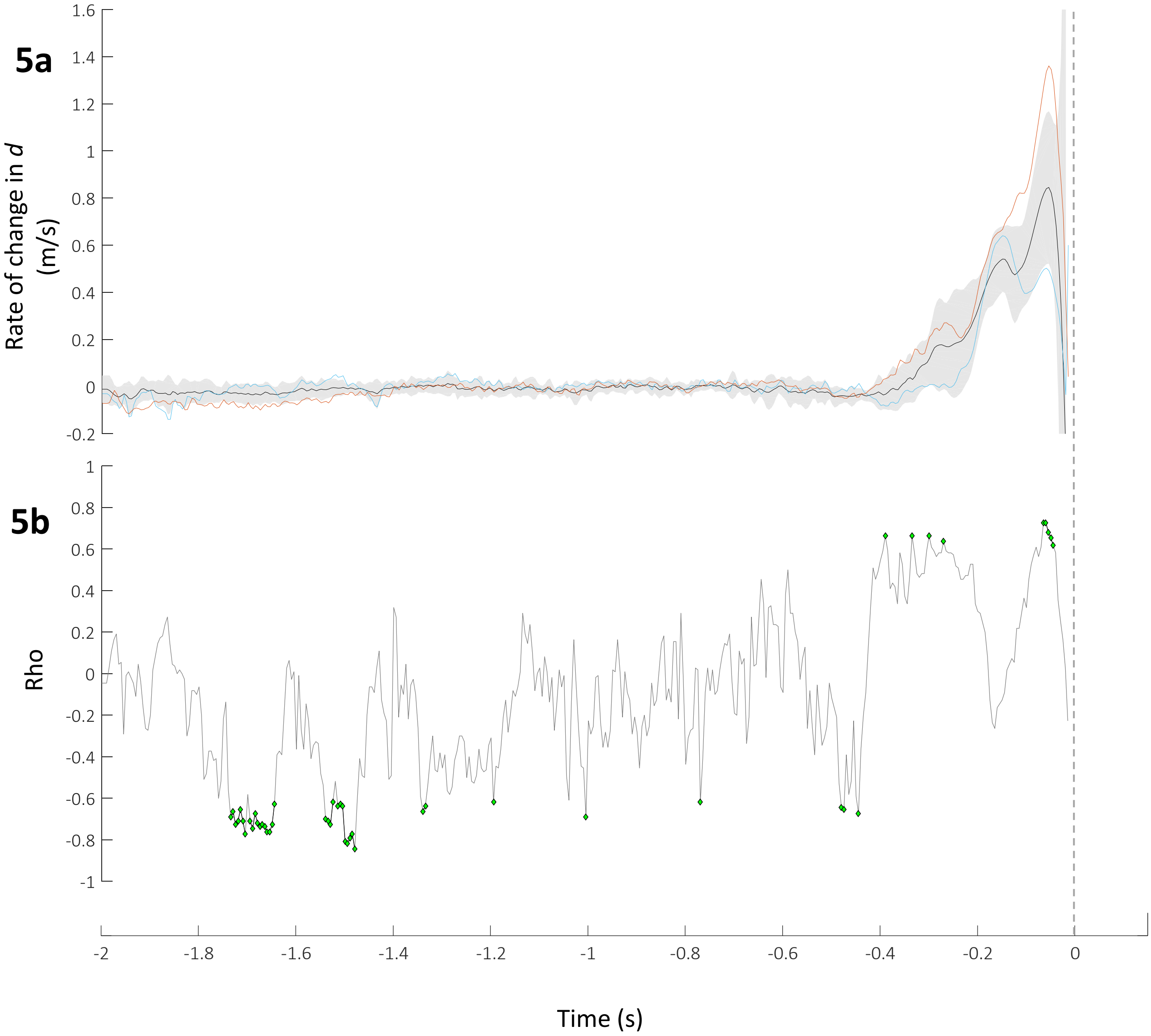


Figure 5.: *Rate of change in d (a) with correlations to performance at corresponding points in time. In (a), black line represents all jumpers, blue line the two best ranked jumpers and red line the two lowest ranked jumpers. Shaded are indicates standard deviations for all jumpers. Time=0 represents take-off. Grey stippled vertical line represents Time=0. Bolded parts of correlation plot (b), represents p-values of <0.05.*

3.4 Summarizing overview

Both the vertical force and the length of *d* were subjects to great change throughout the push-off manoeuvre. In comparison to values of the in-run phase, the typical push-off motion consisted of an elevated level of vertical force with a simultaneous increase in the length of *d*. The push-off normally lasted for approximately 0.4 seconds. On average, athletes typically showed a higher rate of change in *d* during the latter part of the push-off, though this is subject to some individual variations.

Several kinetic parameters associated with the generation of the angular momentum, correlated significantly to performance both during both in-run and push-off. However, the end outcome, the total angular momentum at take-off, did not correlate significantly to performance. Force production correlated significantly to performance during a brief time period of the push-off, whereas peak vertical force did not correlate significantly to performance at all. The length of *d* correlated significantly to performance over longer intervals. Correlations were typically found in the transition phase between in-run and push-off, as well as in brief periods during the latter part of the push-off. To summarize, the better jumpers tended to produce the higher force in a brief period during the early push-off, and have their GRF-vector act closer to their CoM both upon entering and when leaving the push-off phase.

4. Discussion

The purpose of this study was to describe how ski jumpers generate the angular momentum in indoor imitation ski jumping, and how different kinetic parameters of the generation of angular momentum relate to ski jump performance.

This study shows that the angular momentum is being generated in the later part of push-off motion. The late development is essentially linked to the ski jumper's late alteration of *d*: It runs increasingly more posterior to the athletes CoM throughout the entire push-off, with an increase in the rate of change. Eventually, this trigger a greater moment to be created in the later part of the push-off. This, however, only holds if the vertical force does not decline as *d* increases. In this study, the vertical force was found to be greater during the latter phase of the push-off: This further emphasize the late creation of the angular momentum.

Of the kinetic parameters associated with the generation of angular momentum, significant correlations to performance were found in both vertical force production, the length of *d*, and in the rate of change in *d*. Only minor significant correlations were found between force production and performance. Yet, a small trend was still apparent in the data: The better jumpers tended to produce higher force during a brief period early in the push-off. RFD showed no correlation to performance worth mentioning. In analysis between performance and *d,* several wider intervals containing significant correlations occurred. Overall, they implied that the better ranked jumper both entered and left the push-off phase with a value of *d* closer fixated around zero (i.e closer to CoM), whilst having the lower rate of change in *d* during the push-off.

As specified earlier, the vertical force and *d* both plays a role in the generation of the angular momentum: Together they create the moment of which the necessary momentum transpires from. In the current study, the greater force was to a small degree associated with the better performance: All jumpers produced an elevated level of force during the push-off, but the level of force associated with the better performance seemed at times rather random. In other words, the better jumper's executions were not close to relying entirely on the greater force to be the better jump. On the other hand, significant correlations were found for *d* at several time points during both in-run and push-off. The influence of *d* on the angular momentum, however, was not sufficient to create a similar significant correlation for angular momentum. This might be a result of the small trend in force data. That is, since a higher force potentially could nullify the lack of angular momentum created by having the shorter *d*. The reason for this, is the earlier mentioned interplay between the variables.

Several underlying causes might explain why ski jumpers have different solutions in the generation of the angular momentum. For one, the lower ranked athletes could simply not be able to alter *d* in the best possible way. This is based on the notion that the lower ranked athletes would enhance their performance by replicating the better jumper's development of *d*. In such a scenario, one could state that the better jumpers have the better control of *d*, as they are able to develop *d* in a more correct way than the lower ranked jumpers. Eventually, this would mean the force production is subordinate to the orientation of *d*: In order to enhance vertical force, the jumper must first be able to control his or her orientation of *d*. If not, the jumper would simply end up with a wrong level of angular momentum at the take-off. On the other hand, another possible explanation could be that the lower ranked jumpers in fact prefer and need a different development of *d*. That is, one that fits their level of force production the best. This is based on the notion that, by improving force production, a correct orientation of *d* would occur as a product of generating the necessary angular momentum with a certain force. In other words; the level of *d* could merely be a result of the athlete's force production. If so, an additional altering of *d* without first developing the higher force, could result in alarming levels of angular momentum and quite possibly the inferior performance. Recent studies have suggested that in order to improve ski jump performance, one should aim to improve the vertical velocity at jumping take-offs (11, 17). That, in combination with the field of best practice commonly implementing improvement in vertical jumps as part of training goals (11), a possible trend might seem apparent; that ski jumpers acts in order to develop a higher vertical velocity rather than a better control of *d*. Yet, the orientation of *d* is still to be properly investigated, and its relationship to vertical force and skill is so far not completely understood. To conclude, this study displays inter-individual differences in generation of the necessary angular momentum. However, the underlying cause of the differences must be addressed by future studies with different study designs than the current, in order to properly investigate this relationship thoroughly.

Surprisingly, several of the strongest correlations to performance occurred at time points during the in-run phase. The variable that correlated most, also during the in-run, was *d*. In addition, the total angular momentum also correlated significantly to performance during a brief interval of the in-run. The latter is, however, suspected to be a result of the correlations shown in *d*. If vertical force remains static, which it necessarily must do during the in-run, angular momentum merely depends on alteration of *d*. Prior to data analysis, an assumption was that the ski jumpers keep a static position during the in-run. This would mean that their GRF-vectors must have been acting directly through their CoM. If that was the case, the differences in the athlete's *d* would be a product of an offset in the data. Hence, an adjustment of the data seemed appropriate. This would eliminate any offset-related misinterpretation of *d*. Nevertheless, strong correlations to performance were still found. This implies that the jumpers, after the reference time points used to adjust the data (2-1.8s before take-off), alter *d* during the in-run. Thus, the explanation of the phenomenon must be either biomechanical or a result of a systematic error, in which the error would differ between the performance of the subjects. The latter would eventually lead to a false correlation. However, this seemed not particularly likely. A better explanation could be that the jumpers simply were adjusting themselves to enter the push-off phase with an appropriate level of *d*, and did so in different ways, with the better ski jumpers having other solutions than their lower ranked counterparts. For example, the correlation analysis proposing the better jumpers to have values of *d* closer to zero, could possibly be explained by the jumpers acting to minimize rotation prior to the onset of the push-off motion. Overall, it did not seem logical to assume the athletes held a static posture prior to onset of measurement. Thus, in conclusion, the non-adjusted data of *d* seemed valid.

The methodological way of ranking the athletes, should be addressed in brief terms. It is possible to debate whether an actual hill jump competition in connection to the indoor test protocol, would have been the better measure of performance. The outcome of outdoor competitions is frequently subject to weather influence, and to a large degree dependent upon correct equipment and personal knowledge of the hill in which the competition finds place. On the other hand, subjective ranking fully depends on the person(s) responsible for the ranking. In this study, it was not possible to have the athletes partake in an outdoor competition. Thus, other ways to define performance were evaluated, and subjective ranking was considered the most accurate. The ranking process was considered rather uncomplicated as the jumpers held a diverse level. It should be appointed that an objective ranking of the jumpers, in form of the official world ranking (The International Ski Federation, FIS) in ski jumping, was available prior to the test protocol. The objective and subjective ranking differed by the ranking of only one athlete at the actual test day. A choice was made to implement the subjective ranking in the study. It seemed as it was the better choice compared to the objective ranking: The subjective ranking was meant to mirror the performance level of the test day, whereas the objective ranking (FIS) was based upon results from the previous year. During the following winter season, as the objective ranking was updated, the rank lists became similar in order.

Based on the present findings, there seem to be no way to identify correct levels of either variable at the individual level. Thus, in order to relate the variables to skill, correlation analyses were conducted. The ski jump push-off is well recognised as a complex manoeuvre for the ski jumper to perform (1, 3, 10, 18). The current study shows similar findings: Even though the differences in the parameters of the push-off are small and correlations often non-significant, the expected difference in level of performance among the jumpers is extensive. As earlier mentioned, several of the boundary conditions in outdoor ski jumping are different to those of the imitation jump (8-10). Thus, if results of this study were to influence further research or practice in ski jumping, this must be taken under consideration. Also, the need for a similar study on the outdoor ski jump should be appointed. This will better relate findings to the competition setting, as well as further contribute to solving the comprehensive problem of the ski jump; how to get the furthest down the hill.

In conclusion, both d and vertical force showed correlating trends during the push-off. The element that appeared to best distinguish the better jumpers from the lower ranked jumpers, was d. This could be a result of the lower ranked jumpers not being able to produce enough vertical force to keep the same levels of d as the better jumpers. The differences in force production is displayed as a slight significant correlation to performance in the early phase of the push-off. Consequently, after producing the lesser force, the poorer ranked athletes might alter d in order produce the similar angular momentum as the better jumpers. Furthermore, the correlations between d and performance during the in-run phase, might be a result of the better jumper being more able to minimize rotation and keep in balance, upon entering the push-off phase. This study displays how angular momentum is generated in imitation jumps, and what characterize the mechanical solutions of the better jumpers in the current exercise.

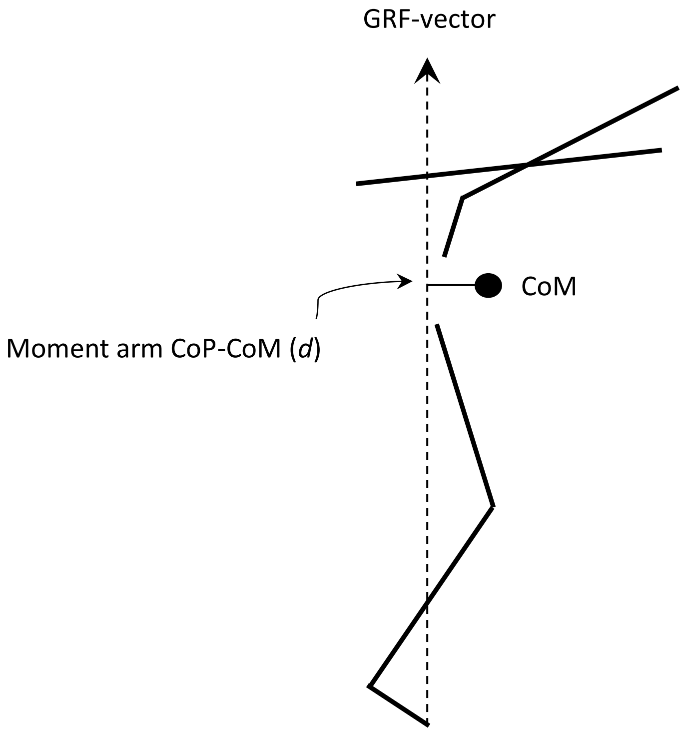
5. References

1. Schwameder H. Biomechanics research in ski jumping, 1991-2006. Sports biomechanics / International Society of Biomechanics in Sports. 2008;7(1):114-36.
2. Arndt A, Brüggemann G-P, Virmavirta M, Komi P. Techniques Used by Olympic Ski Jumpers in the Transition from Takeoff to Early Flight. Journal of Applied Biomechanics. 1995;11(2):224-37.
3. Virmavirta M, Isolehto J, Komi P, Schwameder H, Pigozzi F, Massazza G. Take-off analysis of the Olympic ski jumping competition (HS-106m). Journal of biomechanics. 2009;42(8):1095-101.
4. Schwameder H, Müller E. Biomechanics in ski jumping: A review. European Journal of Sport Science. 2001;1(1):1-16.
5. Ettema G, Hooiveld J, Braaten S, Bobbert M. How do elite ski jumpers handle the dynamic conditions in imitation jumps? Journal of sports sciences. 2016;34(11):1081-7.
6. Komi PV, Virmavirta M. Ski-jumping take-off performance: Determining factors and methodological advances. In: Müller E, Schwameder H, Kornexl E, Raschner C, editors. Science and Skiing. 1th ed. 2-6, Boundary Row, London SE1 8HN, UK: E & FN Spon, Chapman & Hall; 1997. p. 3-26.
7. Virmavirta M, Komi P. The Takeoff Forces in Ski Jumping. Int J Sport Biomechanics. 1989;5(5):248-57.
8. Virmavirta M, Kivekas J, Komi P. Ski jumping takeoff in a wind tunnel with skis. J Appl Biomech. 2011;27(4):375-9.
9. Virmavirta M, Kivekas J, Komi PV. Take-off aerodynamics in ski jumping. Journal of biomechanics. 2001;34(4):465-70.
10. Yamamoto K, Tsubokura M, Ikeda J, Onishi K, Baleriola S. Effect of posture on the aerodynamic characteristics during take-off in ski jumping. Journal of biomechanics. 2016;49(15):3688-96.
11. Pauli CA, Keller M, Ammann F, Hubner K, Lindorfer J, Taylor WR, et al. Kinematics and Kinetics of Squats, Drop Jumps and Imitation Jumps of Ski Jumpers. Journal of strength and conditioning research / National Strength & Conditioning Association. 2016;30(3):643-52.
12. Vaverka F, Janura M, Elfmark M, Salinger J. Inter- and intra-indiividual variability of the ski jumper's take-off. In: Müller E, Schwameder H, Kornexl E, Raschner C, editors. Science and Skiing. 1th ed. 2-6 Boundary Row, London SE1 8HN, UK: E & FN Spon, Champan & Hall; 1997. p. 61-71.
13. Chardonnens J, Favre J, Cuendet F, Gremion G, Aminian K. Measurement of the dynamics in ski jumping using a wearable inertial sensor-based system. Journal of sports sciences. 2014;32(6):591-600.
14. Ettema GJ, Braten S, Bobbert MF. Dynamics of the in-run in ski jumping: a simulation study. J Appl Biomech. 2005;21(3):247-59.
15. Muller W. Determinants of ski-jump performance and implications for health, safety and fairness. Sports medicine (Auckland, NZ). 2009;39(2):85-106.
16. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. Journal of biomechanics. 1996;29(9):1223-30.
17. Golas A, Wilk M, Statsny P, Maszczyk A, Pajerska K, Zajac A. Optimizing Half Squat Post Activation Potential Load In Squat Jump Training For Eliciting Relative Maximal Power In Ski Jumpers. Journal of strength and conditioning research / National Strength & Conditioning Association. 2017.
18. Chardonnens J, Favre J, Cuendet F, Gremion G, Aminian K. Characterization of lower-limbs inter-segment coordination during the take-off extension in ski jumping. Human movement science. 2013;32(4):741-52.

Appendix A

Visual clarification of terms used to describe different the kinetic parameters of the push-off.

A1



Appendix B

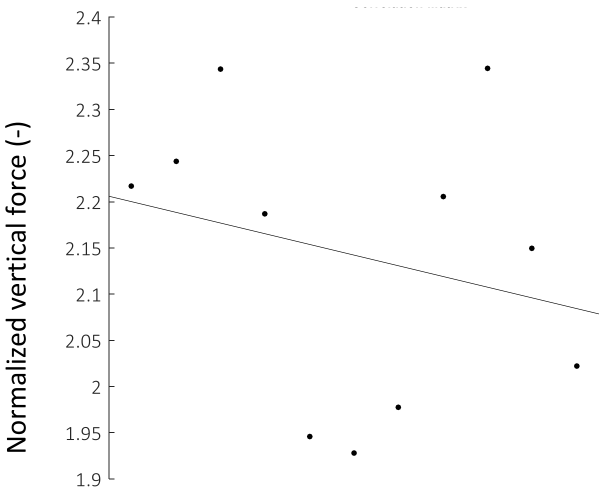
Appendix B1.:

Scatter plot of body-weight normalized peak force and rank.

Rho= -0.2727

p= 0.4182

B1



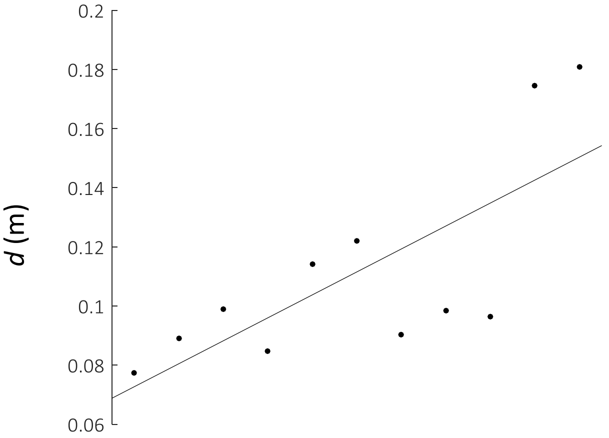
Appendix B2.:

Scatter plot of d and rank at 0.025s before take-off.

Rho= 0.6909

p= 0.0231

B2



Appendix B3.:

Scatter plot of angular momentum and rank at take-off.

Rho= -0.1818

p= 0.595

B3