ANALYSIS OF INTER-SEGMENT COORDINATION DURING THE TAKE-OFF OF SKI JUMPING

1 Julien Chardonnens, 1 Julien Favre, 2 Florian Cuenod, 3 Gérald Gremion and 1 Kamiar Aminian
1Laboratory of Movement Analysis and Measurement (LMAM), EPFL, Lausanne, Switzerland; 2Swiss ski, Bern, Switzerland; 3Swiss Olympic Center, CHUV, Lausanne, Switzerland; email: julien.chardonnens@epfl.ch, web: lmam.epfl.ch

SUMMARY
Take-off is the most important phase in ski jumping. While key spatio-temporal features have been identified during this phase, inter-segment coordination has never been investigated. This study proposed a new approach based on inertial sensors to characterize the coordination between pairs of segments. The continuous relative phases and their descriptive features were automatically calculated for 86 jumps. Reliable patterns of coordination, as well as significant correlations between the proposed features and distance score were obtained. This method highlighted a high potential for performance analysis.

INTRODUCTION
In ski jumping, take-off (TO) is considered as the most important phase since it establishes the initial conditions for the flight. It consists of a rapid extension (about 0.3s), involving the movement of many segments, which tends to produce a vertical ground reaction force and a forward angular momentum [1]. Several spatio-temporal features of this phase (e.g. thigh angular velocity) have been related to performance [2]. Recently, Virmavirta et al. [3] reported two main strategies among the best athletes during TO: 1) active thighs and shanks and a static upper body or 2) active thighs and upper body and static shanks. Nevertheless, the inter-segment coordination, i.e. the motion of a segment relative to another, has never been characterized and compared to performance. The first objective of this study was to propose a method to reliably determine the inter-segment coordination by key features during TO using inertial sensors. The second objective was to evaluate the relationship between these new coordination features and the performance.

METHODS
The measurement system was composed of five small inertial units, including three-dimensional (3D) accelerometer and gyroscope (Physilog®, CH). The units were attached to the shanks, thighs and sacrum segments. 32 male jumpers from Swiss ski team, ranking from world class athletes to juniors, were asked to perform up to three jumps on HS-117 jumping hill in Einsiedeln (CH) while wearing the inertial units. Before each jump, a functional calibration was performed to align the inertial units to the anatomical frames [4]. A distance score was defined for each jump based on the length of the jump and the height of the start platform. By combining the inertial signals, TO phase was identified [5] and the orientations of the segments were calculated during this phase [6]. The segments sagittal angle \( \theta_S \) and angular velocity \( \omega_S \) were normalized over time and amplitude. The phase angle \( \Phi_S \) was determined from the angle \( \theta_S \) vs. the angular velocity \( \omega_S \) in phase plane. Thereafter, to characterize the inter-segment coordination, the continuous relative phase (CRP) [7] was calculated as the difference of phase angle \( \Phi_S \) of proximal and distal segments. Thigh vs. shank and sacrum vs. thigh were considered in this study. The following features were extracted from the CRP curves: mean value \( \mu_{CRP} \) (in deg), maximum \( \max_{CRP} \) and minimum \( \min_{CRP} \) of CRP amplitude (in deg), as well as the temporal occurrence of the maximum \( t_{max} \) and minimum \( t_{min} \) (in % of TO duration). The features of the left and right sides were averaged. Mean and standard deviation of the CRP curves and extracted features were computed for the total number of jumps. To assess the repeatability of CRP pattern, the coefficient of multiple correlation (CMC) was calculated [8]. Finally, Pearson correlation and its level of significance (p-value) between the extracted features and the distance score were evaluated over all the jumps.

RESULTS AND DISCUSSION
In total, CRP curves of thigh-shank and sacrum-thigh pairs were calculated for 86 jumps. A negative CRP was observed for both pairs (Figure 1). This indicated that the distal segment was leaded by the proximal segment in phase plane (i.e., shank leaded by thigh and thigh leaded by sacrum).

Figure 1: Continuous relative phase (CRP) mean (black line) and standard deviation (gray area) over 86 jumps.

CMC of 0.85 and 0.96 were obtained for the thigh-shank and sacrum-thigh CRP, indicating a repeatable pattern with characteristic features. The CRP standard deviations displayed
in Figure 1 reflected the variability related to performance, as well as some noise (e.g. external conditions).

For the thigh-shank pair, the CRP slope was negative until its minimum. This signifies that the thigh moved faster than the shank in phase plane. After the minimum, the phase dynamics was inverted. No local maximum was observed. For the sacrum-thigh pair, the CRP was constant during the first half; so the sacrum and the thigh were moving similarly in phase plane. Then, CRP reached a local minimum indicating that the sacrum was ahead.

The results of the five coordination features for the thigh-shank pair are summarized in Table 1. The highest correlation \((r=-0.35)\) was found for \(\mu_{CRP}\). This suggested that the athletes reaching a higher distance score had the shank more leaded by the thigh in phase plane. We also noticed that these athletes presented almost no shank movement until \(t_{min}\) and were able to delay the beginning of the shank movement \(t_{max} \) and were able to delay the beginning of the shank movement \(t_{min} \), \(r=0.28\). It is worth to note that \(min_{CRP}\) was not related to distance score. Although \(max_{CRP}\) was related to performance \((r=-0.26)\), there was no significant maximum CRP value in the average pattern (Figure 1). This could suggest that the athletes who had a movement of the shank at the beginning of TO, had a lower distance score. Furthermore, although \(t_{max}\) presented a large variation \((±31°)\), it was not correlated to the distance score. This supported the observation regarding the absence of a clear maximum.

**Table 1**: Features extracted for the thigh-shank pair and their correlation coefficient relative to distance score.

<table>
<thead>
<tr>
<th>N=86</th>
<th>(\mu_{CRP})</th>
<th>(max_{CRP})</th>
<th>(t_{max})</th>
<th>(min_{CRP})</th>
<th>(t_{min})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ±SD</td>
<td>-6±4</td>
<td>-5±3</td>
<td>30±31</td>
<td>-21±7</td>
<td>69±6</td>
</tr>
<tr>
<td>Cor. coef. r</td>
<td>-0.35***</td>
<td>-0.26**</td>
<td>NS</td>
<td>NS</td>
<td>0.28**</td>
</tr>
</tbody>
</table>

* p < 0.05; ** p < 0.01; *** p < 0.001; NS p > 0.05

Regarding the coordination features of the sacrum-thigh pair (Table 2), \(t_{max}\) presented the highest correlation \((r=0.28)\) of the five features. Positive correlations were observed for \(\mu_{CRP}\) \((r=0.21)\) and \(min_{CRP}\) \((r=0.21)\). This could indicate that the athletes with a higher distance score minimized the phase between sacrum and thigh segments. On the other hand, the negative correlation observed for \(t_{max}\) could suggest that the best athletes were able to have a dynamic change (i.e. a leading sacrum) faster than the weakest.

**Table 2**: Features extracted for the sacrum-thigh pair and their correlation coefficient with respect to distance score.

<table>
<thead>
<tr>
<th>N=86</th>
<th>(\mu_{CRP})</th>
<th>(max_{CRP})</th>
<th>(t_{max})</th>
<th>(min_{CRP})</th>
<th>(t_{min})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ±SD</td>
<td>-6±8</td>
<td>13±18</td>
<td>58±33</td>
<td>-21±13</td>
<td>56±26</td>
</tr>
<tr>
<td>Cor. coef. r</td>
<td>0.21*</td>
<td>NS</td>
<td>-0.28**</td>
<td>0.22*</td>
<td>NS</td>
</tr>
</tbody>
</table>

* p < 0.05; ** p < 0.01; *** p < 0.001; NS p > 0.05

It is interesting to note that Virmavirta et al. [3] found that some of the best athletes adopted the strategy of a minimum shanks activity combined with a large movement for the thighs and upper body segments. This strategy was in accordance with our results. But, in addition, we noticed that the tuning of coordination timing plays a major role. However, these results should be interpreted with caution due to the small to medium correlation.

**CONCLUSIONS**

A new methodology has been proposed to analyze ski jumping. It characterizes thigh-shank and sacrum-thigh coordination in phase plane. The CRP showed a repeatable pattern and allowed an automatic and systematic extraction of coordination features. The features proposed in this study reported a strong potential for performance evaluation. The mean CRP \((\mu_{CRP})\) for the thigh-shank pair and the temporal occurrence of the minimum \((t_{min})\) for the thigh-shank pair and of the maximum \((t_{max})\) for the sacrum-thigh pair were particularly relevant. In summary, the athletes who obtained a higher distance score showed a shank leaded by the thigh in phase plane as long as possible during TO and were able to precisely tune the coordination between thigh and sacrum.

**ACKNOWLEDGEMENTS**

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**REFERENCES**