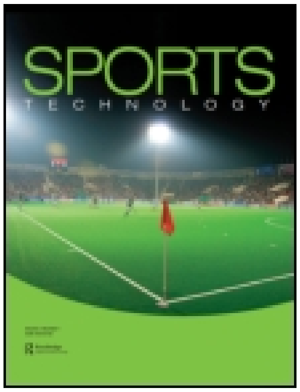

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RESEARCH ARTICLE

Arousal pattern analysis of an Olympic champion in ski jumping

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Abstract
Mental strength is essential to success in many sports disciplines, especially in professional ski jumping. While physiological signals can reveal information on the mental state, their measurement and analysis for elite ski jumping athletes during competition has not been realised. For the first time in professional ski jumping, we investigated heart rate (HR), its temporal pattern, and corresponding body motion in relation to arousal of the Olympic ski jumping gold medallist Simon Ammann during actual competitions, including his Vancouver 2010 Winter Olympics victory. Using a miniature, on-body ECG monitor with integrated acceleration sensor, we collected a dataset of 99 hours length, including 37 hill jumps. Arousal was assessed from HR data conditioned on body position and acceleration data. The HR and its pattern were analysed during competition days, actual jump situations (training, qualification, and competition) and pre-performance routines. HR was related to the competitiveness of the jump situation, even when physical sports performance remained unchanged. Arousal during jumping and pre-performance routines showed highly reproducible HR patterns. The HR pattern, as assessed by dynamic time warping, deviated during the final Olympic jump, at which time the athlete reported difficulties in regulating arousal in his trained manner. Our approach can be used to collect, analyse, and visualise data to assess an athlete's levels and patterns of arousal during typical competitive situations. We believe that data collected in field-based studies with on-body sensing technology could assist in the design of arousal assessment tools and help facilitate top performance levels.

Keywords: *Ski jumping, instrumentation of athletes, on-body sensing, heart rate pattern, arousal, ECG, accelerometer, acceleration, dynamic time warping, sports physiology, sport psychology, gold medallist*

Introduction

Following his success at the 2010 Vancouver Olympics, Swiss athlete Simon Ammann has become the most successful ski jumper in history. However, our measurements confirm that the Olympic victory was at stake just moments before his final jump.

While physical qualifications are an essential prerequisite for top performance, mental strength and the ability to perform under pressure to succeed, in situations requiring the utmost concentration, are also vital (Gould, Greenleaf, Chung, & Guinan, 2002; Nicholls & Polman, 2007). The fact that ski jumping represents a stressful, mentally-challenging situation for many athletes has been recognised through the sport's history. This challenging situation and the pressure to succeed cause arousal, which must be actively regulated in order to be successful (Zaichkowsky & Baltzell, 2001).

Arousal is a psychological construct comprising cognitive (thoughts), affective (feelings), and neurophysiological dimensions, which interact with each other (Zaichkowsky & Baltzell, 2001). Arousal involves the stimulation of the autonomic nervous system (ANS) as a natural response to such stressful situations, and can, among other things, manifest itself as a racing heart (tachycardia) or trembling limbs. These bodily reactions can adversely affect an athlete's concentration and performance. Thus, assessing arousal levels of individual athletes and its

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optimal regulation is key to competition performance enhancement (Landers & Arent, 2006). However, currently no conclusive set-up and realisation exists to objectively assess arousal, and knowledge on arousal measurement and its relation to athlete performance and perception during real competitions is lacking (Oudejans, Kuijpers, Kooijman, & Bakker, 2010; Woodman & Hardy, 2001; Zaichkowsky & Baltzell, 2001).

To investigate the arousal characteristics in professional ski jumping, we measured physiologic signals of an elite athlete for the first time during official competitions. We used a lightweight, unobtrusive on-body sensor to capture body motion and heart activity, which can be associated with arousal, even in naturalistic settings (Myrtek, 2004). Our case study focused on the use of on-body sensing technology to facilitate continuous data recording during an athlete's entire competition day, in particular during jumping and jump pre-performance routines. While this sensor-based approach is not restricted to ski jumping, this sports discipline offers a high degree of structure and reproducibility, and provides an ideal situation to learn about an athlete's individual dynamics of physiological correlates of arousal, which are – for the most part – mediated by non-physical factors. For this purpose, this study aims to:

(1) Present an unobtrusive on-body monitoring solution for ski jumping. With this system, data from seven competitions during the 2009–2010 ski jumping World Cup season, including the 2010 Winter Olympics, were acquired.
(2) Describe methods to analyse heart and motion data of an elite ski jumping athlete during actual jumping and on competition days.
(3) Exemplarily assess temporal patterns of HR during pre-performance routines. Our approach seeks to rank jumps according to differences in arousal regulation during competition situations.

In the past, medication (beta-blocker: Oxprenolol) has been investigated, with some success, as a means of reducing the detrimental effects of bodily arousal when facing the jump situation (Imhof, Blatter, Fuccella, & Turri, 1969). However, later investigation of this medication showed that using it can increase risk of numbness in the legs, potentially jeopardising athlete safety (Videman, Sonck, & Jänne, 1979). Consequently, other approaches to manage arousal were required.

To date, the majority of ski jumping teams benefit from the work of professional sport psychologists, who train athletes to regulate arousal, most importantly during competition situations. Before actual jumping, athletes can regulate arousal by their personal, trained pre-performance routines. Ideally, all pre-performance routines are executed in a consistent, automated and thus highly reproducible fashion. In practice, relevant psychological elements for improving these skills have been identified by interview, observation, or tests and questionnaires. Other psychological conditioning techniques include asking the athletes to verbalise their sensations in a comprehensive and concise fashion (Andersen, 2000). However, to collect relevant data during jumping or during pre-performance routines, these techniques are not appropriate. In contrast, on-body sensing, as considered in our work, allows the continuous recording of heart activity, among other body functions, during sports training and competition situations, without interfering with sports performance.

Continuous monitoring of physiological signals, in particular heart activity, has been sought to complement established sport practices. However, recording this physiological data about elite athletes in practice is subject to unique challenges; in particular the need for unobtrusive, lightweight sensors which the athlete is able and willing to wear even during important competitions (Sands, 2008). In seminal investigations, heart electrocardiogram (ECG) recordings were conducted with two non-professional college student athletes before and after 50 m ski jumping (Hanson & Tabakin, 1964). A radio receiver was placed near the landing area to receive the signals from the radio transmitter, which was attached to the athlete's body. Since that time, however, analysis of heart activity and patterns in ski jumping has not been followed up systematically.

Simultaneous recordings of ECG and 3D acceleration were demonstrated in other sports areas, for example, in skydiving (Hermans & Puers, 2005). A portable module recorded the ECG, air pressure, and 3D body acceleration data from which the free fall period during a test jump could be visually identified. HR peaked during the recording at the time when the athlete jumped out of the airplane. The device's maximum recording time of 14 min required the athlete to start the measurement shortly before the jump.

Heart activity, among other physiological signals, can change during physical activities (daily routine, during competitions) and psychological arousal situations (Iversen, Kupfermann, & Kandel, 2000). To capture their influence without interfering with the athlete's behaviour, day-long recordings are required. Today, advances in instrumentation, sensing technology, miniaturisation, and data analysis provide additional means for physiology-enhanced arousal assessment, even during important competitions such as the Olympic Games.

In contrast to mental arousal investigated in our work, previous sensor-based approaches have assessed the physical aspects of ski jumping (Müller, 2009; Ohgi, Hirai, Murakami, & Seo, 2008; Schwameder, 2008). The collection of relevant data sets in ski jumping often involves high efforts in terms of sensing infrastructure and authentic scenarios, especially in real competitions. Up to now, on-body sensing modalities that work in direct contact with the athlete such as electromyography have been investigated in training hill jumps and laboratory settings only (Schwameder, 2008). Collecting data in laboratory and training environments usually provides more flexibility and control over the sensors' setup, athlete activities, and annotation of relevant episodes. The data collected from competitions, however, reflect the real ski jumping situation and should therefore be considered most valuable. In addition, the World Cup and the Olympic Games, as considered in this work, represent the most important professional competitions. These competitions involve the world's best athletes in top form (Gould & Maynard, 2009; Schwameder et al., 2005).

Methods

A brief introduction to ski jumping

Ski jumping has been an integral part of the Winter Olympic Games since the first Games in 1924. During competition, ski jumping athletes aim to achieve the highest score, which is determined by both jumping distance and style. The athlete must perform complex motion sequences at high speed and on special jump hills, risking serious injuries if motions are not executed properly. The ski jumping sequence comprises the phases of in-run, take-off, flight, landing (telemark position), and out-run. This sequence is depicted in Figure 1.

In-run. The in-run is the area between the in-run gate and the take-off table of a jumping hill. In this part, the athlete gains speed for take-off by crouching, with his knees bent and arms behind the trunk. Owing to this aerodynamic position, jumpers can achieve a take-off speed of more than 100 km/h.

Take-off. The final part of the in-run is straight and inclined at a specific angle. At take-off the athlete thrusts his body upwards by stretching the knees and body. The take-off is considered the most crucial phase as it sets initial conditions for the entire jump performance, for example, velocity and take-off angle (Virmavirta et al., 2009).

Flight. After take-off, the athlete aligns the skis at an angle (V-shape) to gain lift and increase flight time and distance.

Landing. The landing completes the flight when both skis return to the ground. A proper landing includes an artistic element, called telemark. In the telemark position, the athlete bends his knees with distance between the skis, while one ski is further forward than the other. Both arms are stretched out horizontally and face upward.

Out-run. The out-run is the braking area at the end of the landing hill where the athlete slows down and stops. Once stopped, the athlete takes off the skis and clears the way for the next jumper.

To reach the starting position, the athlete ascends the jump hill using a ski lift or elevator. The athlete spends the time before the jump in the waiting area close to the starting gate. During that time, the athlete can perform particular exercises such as stretching, i.e.: exercises to support muscle tone in the legs. As soon as the previous jumper has left the in-run gate, the athlete puts on his skis and prepares to take the in-run gate. The athlete enters his in-run after the ready-to-go signal is released. Until the start of the in-run, the athlete can regulate arousal using

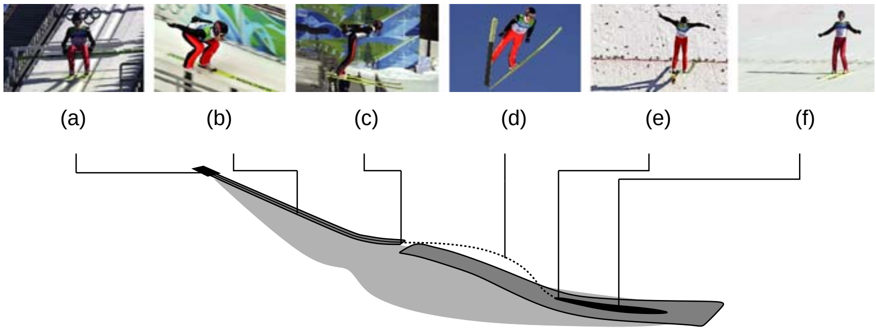

Figure 1. Illustration of a ski jumping hill and tower. Pictures (a)–(f) indicate characteristic ski jumping phases: (a) starting gate and pre-performance routines, (b) in-run, (c) take-off, (d) flight, (e) landing in telemark position, (f) out-run.

his or her personal, self-paced pre-performance routine to focus attention and optimally prepare for the jump, for example, by visualisation techniques.

After trial and qualification rounds, ski jumping competitions consist of two scored rounds, the first round and the final round (plus a third and fourth scored round in the biannual Ski Flying World Championships). Participation in qualification rounds is optional for the top 10 ranked athletes in the World Cup standings in World Cup and Ski Flying competitions (FIS, 2009).

On-body sensor system

From interviews with athletes and coaches, we identified the requirements for the on-body sensor system in ski jumping. HR chest belts, which are commonly used in sports such as running, were not appropriate as the strap around the trunk was considered too restrictive by the athletes. Moreover, keeping the sensor system in place during take-off and landing, when high acceleration forces act upon the jumper, was problematic. The sensor system needed to be lightweight while providing a robust fixation to the athlete's body. In addition, in order to provide a meaningful interpretation of monitor data and distinguish episodes of arousal from those of physical activity, body motion data also needed to be collected.

To this end, we used a commercially-available, miniaturised and lightweight sensor (10 g), comprising of a 2-lead ECG monitor and a 3D accelerometer (Actiwave Cardio, CamNTech Ltd., Cambridge, UK) to record heart activity and body motion simultaneously. The sensor can be comfortably worn beneath an athlete's underwear without interfering with the jump suit. Figure 2 illustrates the sensor and its fixation to the athlete's chest, including the ECG electrodes and the coordinate system of the accelerometer to measure body motion.

The ECG monitor was attached to the athlete's chest using two ECG electrodes (Ag/AgCl, 254 mm^2; Blue Sensor L-00-S, Ambu, Ballerup, Denmark). Sampling rates of 256 Hz and 128 Hz for ECG and acceleration, respectively, allowed for continuous recording of up to 11 h. Our settings facilitated monitoring without interfering with the athlete's preparation procedures during competition situation, as the sensor can be attached several hours before the actual jumping without recharging or downloading the data to a PC. Therefore, our recording strategy featured quick deployment, repeatability, and ease of use so that monitor data could be retrieved without technical supervision, even by the athlete himself in less than 10 min (athlete's report).

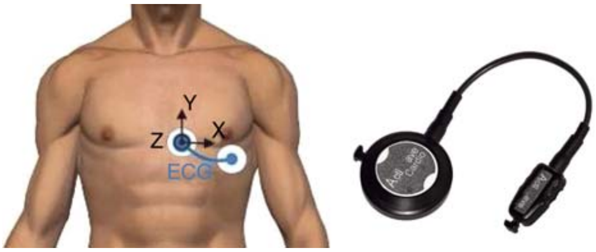

Figure 2. Illustration of the ECG monitor attachment to the athlete's chest. Arrows x, y, and z indicate the coordinate system of the integrated 3D accelerometer.

Data recording procedure

In cooperation with the Swiss ski jumping team, we collected multiple recordings during the ski jumping season 2009–2010 from the elite athlete Simon Ammann. During that season, he won the World Cup, the Winter Olympics, and the Ski Flying World Championships.

Data set

For our data set, we recorded the athlete's activities on 12 individual days, including one individual training session, five official World Cup competitions, the Winter Olympics large hill (LH) competition, the Ski Flying World Championships, and numerous qualification rounds (including trial rounds) for each of the individual competitions. In total, we obtained a data set of 99 hours including a total of 37 jumps, six jumps during training, 15 jumps during qualification (including trial rounds), and 16 jumps during competition situation (scored rounds).

Recording during training. During one training session, we introduced our monitoring approach and let the athlete familiarise himself with the sensor system. This training took place at the athlete's home training site, the large hill in Einsiedeln, Switzerland. The training provided us with the flexibility to test and adapt the system to match the athlete's needs, including optimal device placement on the athlete's chest so that it did not interfere with his activities. In the training, the athlete followed his regular exercise schedule of six jumps, one jump every 15–25 min. In order not to interfere with the athlete's training activities, we attached the sensor before warming-up and detached it after completing the last jump. The total recording time during this training session was 2 h. After this training, the athlete was able to apply the sensor system by himself.

Recording during competitions. The athlete conducted recordings at official FIS competitions. Table I summarises the competitions and corresponding

Table I. Summary of competitions at which we recorded and analysed the athlete's heart activity and body motion, including competition name (WC: World Cup, OL: Olympics), type (SF: ski flying, LH: large hill), location, total score, rank, and number of jumps in qualification, including trials (Q), and competition situation (C).

					Num. jumps	
Competition	Type	Location	Total points	Rank	Q	C
WC1	LH	Engelberg, Switzerland	270.4	1	1	2
WC2	LH	Engelberg, Switzerland	264.6	2	1	2
WC3	SF	Oberstdorf, Germany	415.2	4	4	2
WC4	LH	Klingenthal, Germany	263.9	1	1	2
WC5	LH	Oslo, Norway	267.7	1	1	2
WC6	SF	Planica, Slovenia	935.8	1	4	4
OL	LH	Vancouver, Canada	283.6	1	3	2

results of the athlete, including hill type, location, total points, rank, and number of jumps in qualification and competition situation. The athlete arbitrarily selected these competitions to conduct the recordings according to his preference and commitment.

In order not to interfere with his habitual preparations and exercise routine, he attached the sensor system in the morning, several hours before the start of the competition; and detached it in the evening, after the end of the competition. The average recording time was 8 hours per day. This procedure was repeated by the athlete on each recording day.

Activity diary for data annotation. To determine sections in the data which were relevant for our analysis, an activity diary including jumping times and preparation periods of the athlete during training and competition was recorded by a member of the Swiss ski jumping team who could follow the athlete. At the end of the recording day, the data were transferred from the sensor to a PC via the sensor's USB docking station. During international competitions, the athlete uploaded the recorded data and diaries via a web interface to our server.

Analysis procedure

To identify episodes of arousal during the day, HR alone could be misleading, as physical activity acts as a confounding variable. The athlete's competition day included various physical activities besides the jump. We thus analysed HR and body motion jointly with the athlete's activity diary. For data annotation and analysis we used Matlab.

Computation of HR and body motion. For the analysis of the arousal characteristics, we computed the HR from the ECG signal. For this purpose, we used a free implementation of the Pan-Tompkins-Hamilton algorithm (http://www.eplimited.com; Hamilton & Tompkins, 1986). We subsequently interpolated and low-pass filtered (2nd order Butterworth, cut-off frequency 0.3 Hz) the series of detected heart beats to obtain a uniformly sampled time series, matching the sampling of the corresponding body acceleration signal for alignment.

To obtain an indicator of body motion, we computed the resulting body acceleration vector from the three high-pass filtered (2nd order Butterworth filter, cut-off frequency 0.1 Hz) acceleration axes x, y, and z, as used in previous psychophysiological studies (Myrtek, Foerster, & Brügner, 2001).

Data annotation. For our analysis, we manually annotated the ski jumping phases in-run, flight, and out-run of every jump with the help of the athlete's activity diary and corresponding body acceleration signal. The annotation also provided means to align all the jumps' monitored data to a common reference in time for comparison, for example: the start of the in-run. In addition, we annotated the time of the athlete's personal pre-performance routine.

Supplementary athlete feedback. In addition to the recorded sensor data, we collected athlete feedback as supplementary information during the established athlete coaching process after the season by the athlete's professional sport psychologist. Although, athlete feedback is not required for our analysis procedure, we used this supplementary information to also assess correspondence of measured arousal to the athlete's sensation. This feedback included (1) a questionnaire on arousal felt during jumping: in training, qualification (including trials), and competition situations (with 1 = no arousal, 10 = extreme arousal); and (2) an interview to identify the jump where the athlete felt that his arousal regulation routine deviated most from his familiar, trained manner. For this purpose, video recordings of each of the 16 recorded competition jumps during that season were also used.

Statistical analysis. The difference in mean HR between jumping situations (training, qualification, and competition) was investigated using the Wilcoxon signed rank test (two-sided). The alpha level was set to $P < 0.05$. This test required the tested sample vectors to have equal lengths. We tested 15 mean HR samples of the qualification situation against 15 mean HR samples of the competition situation (leaving out the first of the 16 mean HR samples). The test was not performed for the training situation as only six mean HR samples were available.

Analysis of arousal levels during jumping. We analysed mean HR during jumping. Therefore, we computed the mean HR on the annotated jump phases: in-run, flight, and out-run, for each of the three jump situations: training, qualification (including trials), and competition. In addition, the supplementary athlete feedback was used to assess correspondence of the measured mean HR to the athlete's reported levels of arousal during jumping.

Analysis of arousal patterns during pre-performance routines. We analysed dissimilarity of HR patterns of the athlete's personal pre-performance routine during competition situations, which included the time immediately before each jump, from after putting on the skis until starting the in-run. Although the length of the pre-performance routine is constrained by the official competition protocol, the actual duration of these activities can vary naturally. Therefore, we used a method from time series analysis that can measure pattern dissimilarity for patterns with different lengths, called dynamic time warping (DTW).

Dynamic Time Warping (DTW). DTW has emerged in the field of speech recognition (Sakoe & Chiba, 1978) and has been applied to problems in different engineering domains, such as data mining and gesture recognition. In contrast to manual, visual inspection, DTW provides a means to derive an objective, reproducible ordering of dissimilarity on a set of HR patterns. DTW calculates the distance between two patterns of time series data, using a non-linear mapping. This non-linear mapping of patterns $A = \{a_1, \ldots, a_N\}$ and $B = \{b_1, \ldots, b_M\}$ of length N and M, respectively, is called warping. The DTW distance (also called cost), DTW(A,B) between pattern A and B, is defined as the warping path with minimum total cost:

$$DTW(A,B) = \min\left\{\sum_{k=1}^{K} w_k(a,b)\right\} \tag{1}$$

The warping path w is computed from the $\mathrm{N} \times \mathrm{M}$ cost matrix of the patterns A and B, using a dynamic programming algorithm. For a detailed explanation of the DTW algorithm see Sakoe and Chiba (1978).

Figure 3 shows an example of two HR patterns of different length, the non-linear alignment between them, and the corresponding cost matrix including the warping path of minimum total costs.

For DTW analysis of HR patterns, we included all combinations of pair-wise pattern comparisons, where each of the N HR patterns is compared to N-1 patterns. For N patterns, there are $\binom{N}{2}$ pair-wise combinations, creating an $\mathrm{N} \times \mathrm{N}$ DTW distance matrix, symmetric at the main diagonal (due to the DTW symmetry property). Increasing DTW costs indicate higher dissimilarity of patterns. The self-dissimilarity (main diagonal) of a pattern is always zero. To compare warping paths, the warping costs are normalised to the warping path length.

To obtain an overall ranking of dissimilarity on the set of N HR patterns, we ranked each 1-to-N comparison in descending order of their DTW distance, excluding the self-dissimilarity. Subsequently, we computed the mean rank for each of the N patterns to derive an aggregated order of

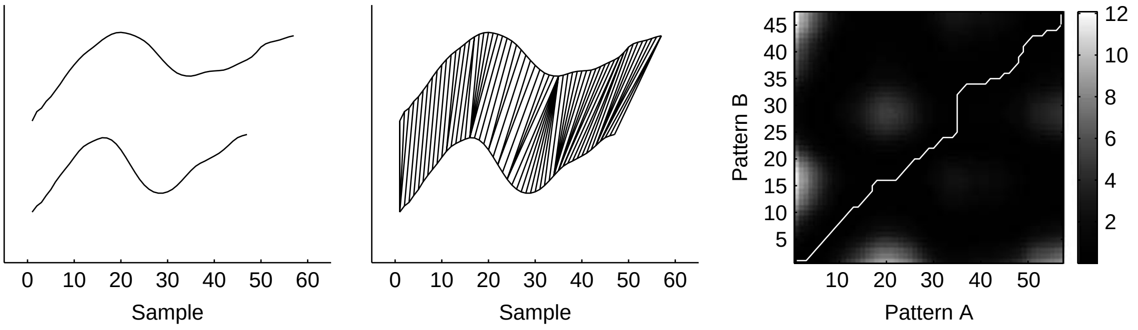

Figure 3. Example of the DTW algorithm operation showing the two HR patterns A and B for comparison (left), the non-linear DTW alignment between them (centre), and the corresponding DTW cost matrix including the warping path with minimum total costs (right). Brightness indicates costs (distances): black = low costs, white = high costs.

within-set dissimilarity. The resulting order gives a notion of which HR patterns deviate most from the average shape of patterns in the set, thus providing an insight into how arousal differs between individual jumps.

Results

We analysed arousal from the data collected. In this section, we first present our results on arousal characteristics during competition days and specific activities of the athlete's daily routine to distinguish episodes of arousal from physical activity. Subsequently, we describe the levels and pattern of arousal during the phases of ski jumping with respect to different levels of competitiveness in training, qualification and competition situations. Finally, we analysed HR patterns to identify and quantify deviations of arousal during the athlete's trained pre-performance routine during competition situations.

Arousal during competition days

Figure 4 shows an example of a low-pass filtered representation of HR and body motion (ACC) of the chest acceleration during two World Cup competition days. During both days, the athlete followed the same habitual schedule of activities and exercises.

As expected, the HR increased during physical activity (warm-up exercises labelled with 1) for example, between 10am and 11am, and 30 min before each jump. During this elevated physical activity, mean HR increased up to a maximum of 160 beats·min^{-1} (BPM).

In addition, three prominent mean HR peaks of up to 160 BPM can be identified (episodes labelled with 2) where no comparably extensive body motion was measured. These peaks belong to the strongest physiological arousal during the day and coincided with jumping times. Physical activity during jumping was lower compared to warm-up and other pre-jump exercise periods, and lasted for a few seconds of the actual jumping motion only. According to the athlete's diary, the athlete practiced with his coach the motion sequence of jumping throughout the day with comparable muscle tension, which indicated that the motion sequence and muscle tension itself did not cause the elevated HR, rather that was measured during jumping. Consequently, we linked these three prominent HR peaks to episodes of arousal.

Arousal levels and pattern during jumping

The athlete reported different levels of arousal felt during jumping under increasingly competitive conditions (training: 5, qualification: 8, competition: 10; with 1 = no arousal, 10 = extreme arousal). Measured differences in mean HR during jumping in training, qualification, and competition situations confirmed the arousal differences, as reported by the athlete.

Figure 5 shows the mean HR and body motion dynamics during training, qualification, and competition situations with respect to the jump phases of in-run, flight, and out-run. Independent of the actual competitive situation, the athlete performed the same physical exercises, confirmed by the chest accelerations measured. Note that measured elevated motion dynamics during the training situation resulted from

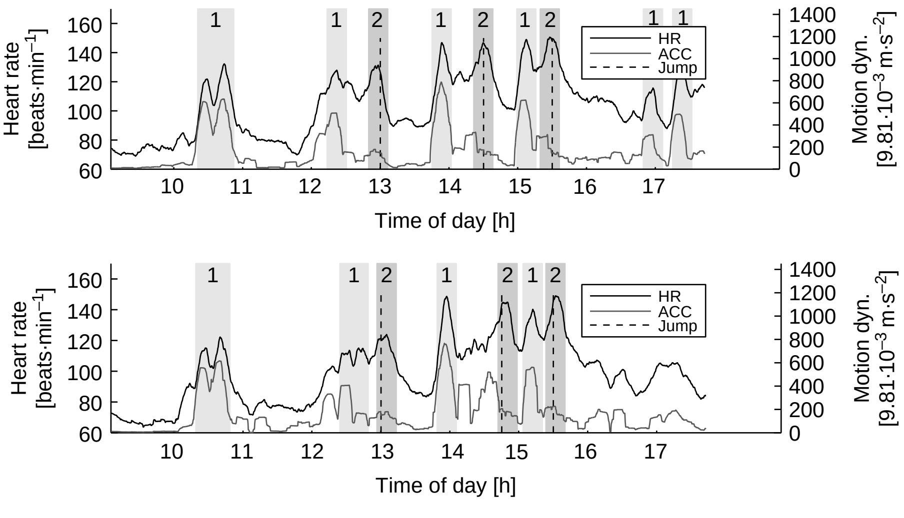

Figure 4. Example of HR and ACC during World Cup A (top) and World Cup B (bottom). The athlete followed the same schedule of activities during these competition days. Note the resemblance in the temporal patterns of the two different competition days. The highlighted periods indicate elevated HR with an increase in ACC (label 1), and without an increase in ACC (label 2). Label 2 coincides with jumping.

increased surface roughness due to a grass mat underground instead of snow. Nonetheless, the mean HR was higher during competition situation as compared to the training and qualification situations. While the mean HR is unchanged between in-run and flight, it was higher during out-run in training, qualification, and competition. The mean HR and its standard deviation during jumping (including in-run, flight, and out-run) was 118 ± 5 BPM during training, 152 ± 11 BPM during qualification, and 168 ± 6 BPM during competition. The mean HR differences were significant between qualification and competition (Wilcoxon signed rank test, $P < 0.001$, signed rank = 6). The mean HR level during training was lower than the qualification level. However, the statistical significance was not tested due to the low number of samples available for training.

While the mean HR exhibited a relation to the athlete's perception of arousal, the temporal HR pattern during jumping allowed us to identify additional characteristics of arousal across time, and to associate HR patterns with ski jumping phases. Figure 6 shows the recorded HR during three arbitrarily selected jumps in training and World Cup competitions, ranging from 45 s before to 45 s after start of the in-run. From the mean HR, one can visually differentiate between jumps belonging to either training or competition situations. In addition, the HR follows a characteristic pattern, which is detailed later in this article.

Figures 7 and 8 depict typical examples of HR pattern and the corresponding body acceleration pattern, observed during a competition jump (cf. orientation of the acceleration sensor in Figure 2).

Before the in-run, the athlete sat in an upright position at the in-run gate (y-axis acceleration of $g = -9.81 \mathrm{m \cdot s^{-2}}$; Figure 7, label 1). During in-run, the athlete bent his trunk parallel to the skis and formed a tucked, aerodynamic position (level shift in the y- and z-axis acceleration). The magnitude of the z-axis acceleration increased as the athlete gained speed at the concave end of the in-run (Figure 7, label 2). The athlete initiated the take-off motion by lifting the trunk followed by a powerful jump (spike of $\pm 3 \cdot g$ in the y- and z-axis acceleration; Figure 7, label 3) to enter the flight phase (x- and y-axis acceleration returned to zero level, z-axis acceleration steadily increased up to g; Figure 7, label 4). Subsequently, the skis hit the ground at landing (spikes up to $-4 \cdot g$ in the y- and z-axis acceleration; Figure 7, label 5). After landing, the skier kept the trunk in an upright position during out-run, while slowing down until stop (Figure 7, label 6). Towards the end of the out-run the skier performed typical braking movements with the skis (displacement in the y-axis acceleration; Figure 7, label 7). Finally, the athlete stopped, bent his trunk forward, and took off his skis (Figure 7, label 8).

w>From the 3D acceleration pattern, we associated the jumping phases and key events to the HR pattern during jumping. The HR pattern (cf. Figure 8), compared with the 3D acceleration pattern, exhibited fewer associations to the ski jumping phases and key events. However, changes in HR coincided with postural changes during in-run and flight. When the athlete bent his trunk forward during the in-run, the HR decreased shortly afterwards (Figure 8, label 1). At take-off, the athlete quickly lifted his trunk from the tucked position and the HR increased simultaneously (Figure 8, label 2). During the flight phase, the HR continued to rise and peaked at the end of the out-run (Figure 8, label 3), gradually declining thereafter. After the athlete had bent his trunk to take off his skis, the HR dropped again (Figure 8, label 4). We observed the highest HRs during out-run, about 25 s after the start of the in-run. Lowest HRs occurred at the initialisation of the flight phase. While the HR rose immediately when the athlete lifted his upper body at take-off, it showed a lag in decreasing of about 2 s when he tucked during in-run or when he took off his skis at the end of the out-run. For this athlete, the HR pattern occurred reproducibly, independent of the training or competition situation (cf. Figure 6).

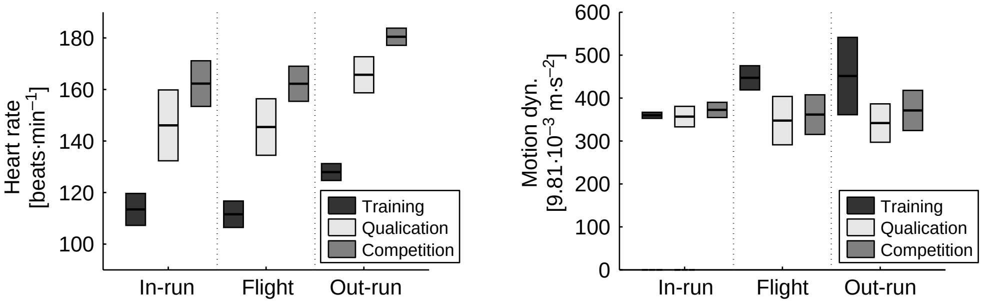

Figure 5. Mean HR (left) and body motion dynamics (right) in training, qualification, and competition situation during in-run, flight, and out-run. The boxes represent mean values and their standard deviation. The mean HR differed significantly (Wilcoxon signed rank test, $P < 0.001$, signed rank = 6) between qualification and competition situations.

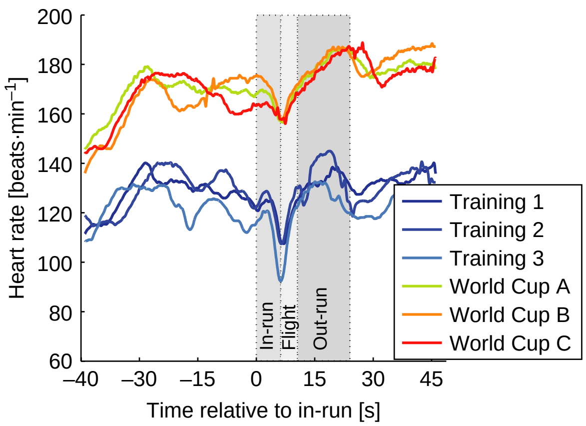

Figure 6. HR during three arbitrary jumps in training and competition situations, including the average duration of the ski jumping phases of in-run, flight, and out-run. Please note that for clarity, we omitted jumps in qualification and only show either extremes of lowest or highest arousal-level difference. All jumps exhibit a characteristic HR pattern (cf. Figure 8) during in-run, flight, and out-run, independent of the jump situation (training or competition).

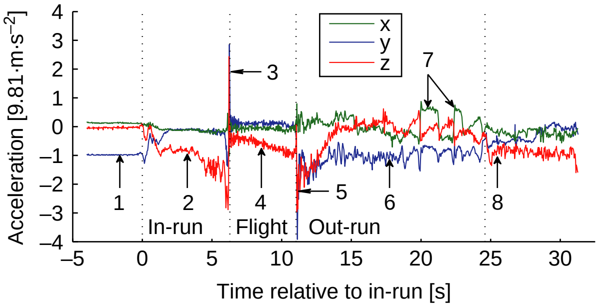

Figure 7. Typical pattern of upper body acceleration in x-,y-,and z-direction during a jump. The numbers indicate ski jumping phases and events: (1) starting position (pre-performance routine), (2) in-run, (3) take-off, (4) flight, (5) landing, (6) out-run, (7) braking movements, (8) taking off skis.

Arousal patterns during pre-performance routines

Figure 9 shows the standardised ($\mu = 0$, $\sigma = 1$) HR patterns of the 16 pre-performance routines (the time after putting on the skis until starting of the in-run) during competition situation used for DTW analysis.

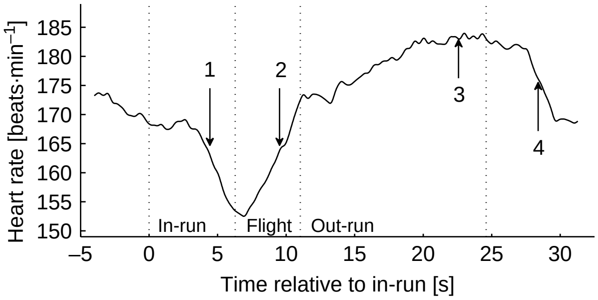

Figure 8. Typical pattern of HR during a jump. The numbers indicate prominent ski jumping phases and events: (1) HR drop during in-run, (2) HR jump up during flight, (3) HR peaks above 180 beats·min^{-1} at the end of the out-run, (4) HR drops when the athlete takes off his skis.

Figure 10 shows the corresponding normalised DTW cost matrix obtained by the pair-wise comparison of HR patterns of all 16 competition jumps. The jumps WC6-R1 and WC5-R1 showed highest dissimilarity (higher DTW distances) compared to all other jumps. This dissimilarity of the jumps WC6- R1 and WC5-R1 could be explained by the particular motion and external influences that perturbed the arousal during the pre-performance routine. In WC6-R1 the athlete's HR dropped again after he had finished putting on his skis (about 20 s before taking the in-run gate). Visual inspection of the motion data revealed that the athlete also bent his trunk at that time. During WC5-R1 the athlete had to wait approximately four times longer to start his in-run than during the other competitions, due to hazardous wind conditions. During that waiting time, HR steadily decreased, identified as a pattern deviation by DTW.

To investigate whether patterns that originated from psychological deviations could be identified by DTW, we performed the DTW analysis and ranked the results according to the dissimilarity, excluding WC6-R1 and WC5- R1. The DTW analysis without WC6-R1 and WC5-R1 showed a lower mean dissimilarity of HR patterns as indicated by the decrease in mean DTW costs from 0.199 to 0.146. Figure 11 illustrates the rankings derived from both DTW analyses. Dissimilarity rank 1 corresponds to

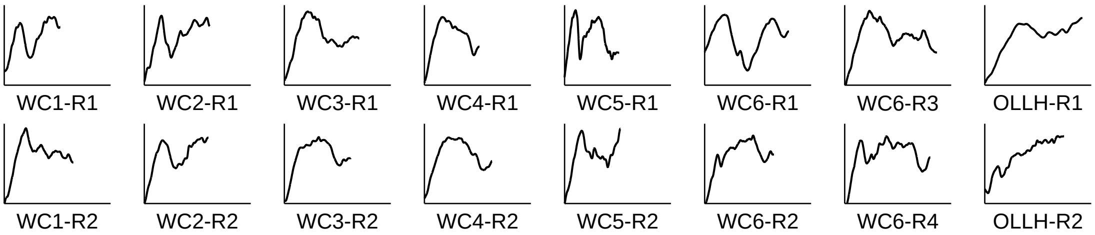

Figure 9. Standardised ($\mu = 0$, $\sigma = 1$) HR patterns of the 16 pre-performance routines (after putting on the skis until starting the in-run; WC = World Cup, OL = Olympics, R = Round) during competition situation used for DTW analysis.

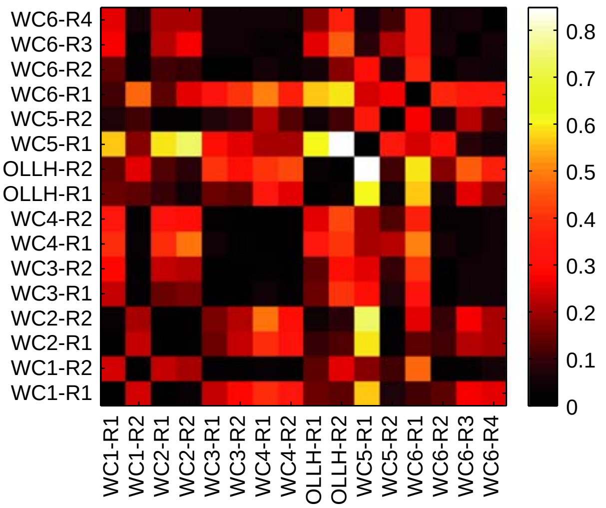

Figure 10. Matrix of normalised DTW distances of pair-wise comparisons of the 16 HR patterns during the pre-performance routine (after putting on the skis until starting the in-run; WC = World Cup, OL = Olympics, R = Round) during competition situation. Brighter patches (higher DTW distances) indicate larger dissimilarity, most prominently WC6-R1 and WC5-R1. Less dissimilar patterns appear as dark patches (lower DTW distances).

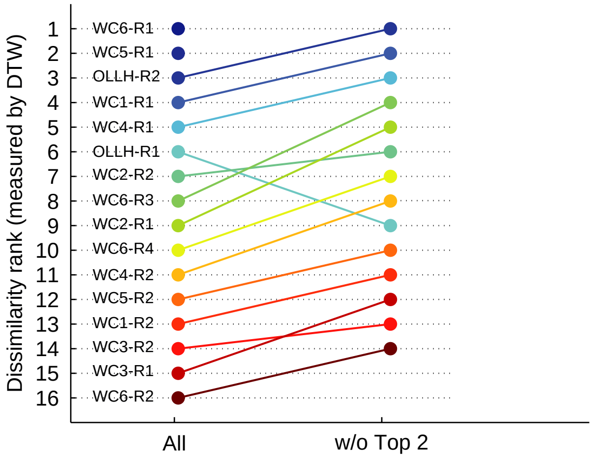

Figure 11. Ranking of jumps according to the HR pattern dissimilarity calculated with DTW, including all 16 competition jumps (left) and all competition jumps without WC6-R1 and WC5-R1 (right). See text for further details. Dissimilarity rank 1 corresponds to the highest dissimilarity in the set of competition recordings.

the highest dissimilarity in the set of competition recordings.

With this modification, OLLH-R2 was identified as most dissimilar (dissimilarity rank 1) compared with all other jumps, which matches the athlete's sensation. The athlete reported impaired arousal regulation until the start of the in-run during the final jump of the large hill 2010 Winter Olympics competition. Although the mean HR of that particular jump did not differ from the other competition jumps, a distinct HR pattern reflected this sensation. This HR pattern does not exhibit a sharp increase after the athlete put on his skis; instead a steady increase in HR until start of the in-run was measured, which was ranked most dissimilar by the DTW. In the corresponding ranking of Figure 11, all HR patterns but one (OLLH-R1) increased their dissimilarity rank and thus show OLLH-R2 as most dissimilar. In this analysis, OLLH-R1 changed from rank 6 to 9, and thus became less dissimilar compared to other jumps. This change could be attributed to the reduced DTW analysis set, since WC6-R1 and WC5-R1 were removed. Based on these results, we conclude that this ranking can capture arousal patterns of psychological origin, in particular, through top-ranked jumps.

Discussion

The assessment of arousal and its physiological correlates is complex and lacks a conclusive and established methodology for its measurement, including changes depending on situational differences (for example, training vs. competition). Our methodological case study of the 2010 World and Olympic ski jumping champion demonstrates the technical feasibility of continuous recording of HR and body motion for further analysis. Our approach confirms a strategy to (1) collect data during different jump situations throughout the competition season, (2) learn about an athlete's individual variation in physiological correlates of arousal during different jump situations, while also considering his verbalised sensation, and (3) assess HR patterns, which is considered a novel approach in the assessment of pre-performance routines in this work. Our work does not extend to predicting future performances of the monitored athlete. As only one athlete was studied, a larger trial with more participants would be needed before more general conclusions can be drawn.

From visual inspection of our day-long measurements and HR patterns, we identified and described two arousal states of predominantly either physical or psychological origin during competition days. Peak levels of HR were associated with the corresponding high (physical origin) or low (psychological origin) level of body motion. Arousal showed a clear relation to jump events, when highest HR of the competition day was recorded, which exceeded the HR measured during physical activity. The need to distinguish between HR of physical and psychological origin during the day to determine episodes of arousal had been recognised in earlier work, not related to ski jumping and sports (Myrtek et al., 2001).

We demonstrated our data to the athlete and coaches. The visualisation (cf. Figure 4 and Figure 6) of our day-long measurements and HR patterns during and before jumping was considered valuable information to both the coaches and the athlete. The experts felt our approach provided previously unknown insights into the athlete's arousal, which might contribute to the design of future, individual recreation strategies during competition days.

The increasing arousal level from training to qualification (including trials) and competition can be interpreted by the level of competitiveness of the jump situation. While training and competition situations represented the lowest and highest levels of competitiveness and arousal, qualification ranged in between these two extreme situations. Because the athlete was ranked within the top ten in the World Cup and was always prequalified for competition, the result of the qualification did not jeopardise his participation in competition and thus might have lowered the pressure to perform, in other words, the arousal level. According to the athlete, qualification and trial jumps also served the purpose of testing modifications to the equipment or jump suit. Consequently, the athlete considered jumps in qualification and trial rounds as additional training, yet he was aware of the competitive environment, being different from individual training in his familiar environment.

In addition to the arousal level during jumping, the arousal pattern (HR decrease during in-run, increase and culmination during flight and out-run, cf. Figure 8) was found to be consistent and independent of the training, qualification, and competition situations. Preliminary analyses of data from other athletes in the Swiss ski jumping team indicated that their arousal patterns replicate the observations presented here. There is evidence that this arousal pattern during jumping is in part mediated by body posture as well as psychophysiological processes (Rajendra, Kannathal, Lee, & Leong, 2005), for example, the release of catecholamines during flight, which stimulate the heart's activity (Imhof et al., 1969). However, the origin of both contributions (i.e. the changes in arousal and the changes in body posture) to the observed HR pattern during jumping is unknown. As professional ski jumping athletes always perform the same trained and highly automated sequence of motions during jumping, it seems reasonable to attribute the observed changes during jumping predominantly to changes in arousal.

To investigate arousal before jumping, we compared patterns of HR during the athlete's personal pre-performance routines in competition situations. Trained personal pre-performance routines are considered important for arousal regulation and optimal performance in competitions (Singer, 2002). In this study, we considered the athlete's pre-performance routine during the time after putting on the skis until starting the in-run. During this time period, the athlete always adhered to his pre-performance routine in a highly automated and reproducible fashion. Body motion, which could affect arousal measurement, was limited to the activities: taking the in-run gate, checking the binding, and sitting at the in-run gate awaiting the ready-to-go signal. Therefore, the HR patterns during this time period of the athlete's personal pre-performance routine were investigated to interpret arousal.

Our DTW-based assessment of pattern dissimilarity quantified degrees of changes in HR patterns during the athlete's pre-performance routine. The ranking scheme after DTW pattern assessment was confirmed by the athlete's own report of impaired arousal regulation during the pre-performance routine of his final Olympic jump.

The arousal pattern was investigated in a precisely defined time section when pre-performance routines were expected to be hardly influenced by external events. Nevertheless, the comparison of HR patterns requires careful interpretation since deviations in habitual physical activity and competition protocol could affect the DTW analysis.

Arousal assessment and its regulation is an important topic in sport psychology and frequently discussed independent of a specific sports discipline. For this purpose, our recording and analysis approach could be used to analyse changes in arousal during pre-performance routines and actual sports performance with respect to situational differences (for example, training and competition).

Individual sports, in contrast to team sports, can facilitate attributing physiological correlates of changes in arousal to psychological origins of monitored heart activity and body motion data (for example, diving, golf, shooting, and ski jumping). In these sports, the actual body motion sequences are rather short in comparison to the total duration of the competition, mainly self-determined, and hardly depending on external influences (for example, interaction with team members).

Furthermore, our arousal analysis could also be used to provide a form of feedback to the athlete (sometimes referred to as *biofeedback*) and therefore be a useful tool for coaching, for example, in establishing and assessing individual pre-performance routines during competitions.

Conclusion

In this work we analysed physiological data related to arousal of the Swiss elite ski jumping athlete Simon Ammann using on-body sensing. We recorded heart activity and body motion during actual World Cup competitions, including his 2010 Winter Olympics victory. To the best of our knowledge, the collected data set is the first of its kind in professional ski jumping.

The measurements revealed a clear relationship between competitiveness of the jump situation and HR level, across jumps during training, qualification, and competition situations. During jumping, the physical sports performance remained unchanged. The HR showed a distinct temporal pattern during the phases of ski jumping, which was consistent in each jump situation. Our DTW-based analysis of HR patterns during pre-performance routines identified a deviation that was related to an impaired arousal regulation, as confirmed by the athlete.

In the future, we plan to continue and expand our monitoring with Simon Ammann and systematically include other athletes on a regular basis. We believe that our work could encourage similar endeavours to collect and analyse relevant data from elite athletes using body-worn sensors during training and competition. We expect that other sports disciplines could benefit from this monitoring and analysis approach as an aid to facilitating top performance beyond pure physical skills training.

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