DIFFERENCES BETWEEN PARALLEL SKIING AND CARVING BASED ON WEARABLE SENSOR DATA AND TECHNIQUE ANALYSIS ALGORITHMS

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The purpose of this study was to objectively identify differences between conventional parallel skiing (side-skidding) and carving (no side-skidding) with regard to selected movement actions of the upper body and their influences on movement stability. Comparison of the two skiing styles is approached by a set of quantifiable technique metrics (lateral, horizontal and rotational movement of the upper body), extracted as principal components (PCs) from whole-body wearable sensor data of highly experienced skiers (n=20). Stability was quantified through normalized jerk scores. Carving involved increased angulation of the hip in the transition phase, a more posterior body posture over the whole skiing turn cycle, and less upper body rotation in the steering phase. In all technique elements carving was more stable (lower jerk score) compared to parallel ski steering.

KEYWORDS: alpine skiing, technique element, inertial measurement unit IMU, principal component analysis PCA, human movement analysis.

INTRODUCTION: Alpine skiing is a dynamic, high-speed sport characterized by a gliding ski-snow interaction. The uncommon interaction places high demands on the motor control system, resulting in different movement actions and techniques (LeMaster, 2010).
Technique guidelines have been developed (Austrian Ski School Association, 2015; German Ski Instructors Association, 2019), which include definitions of different levels, that should be passed along the skiing educational path. The two major levels are the parallel (turning with side-skidding) and the carving (skis cutting through the snow with minimal side-skidding) turn techniques. Although the techniques are essentially different, adaptive movement actions within them can be broken down to the same technical elements (Loland, 2009): e.g. lateral, horizontal, vertical body weight shift and rotation of the upper body. Differences in these elements with regard to the main techniques have been reported by practitioners (Austrian Ski School Association, 2015; German Ski Instructors Association, 2019), e.g. less upper body rotation is required while carving since the waist of the skis dictates the turn already. However, in the authors' perspective, a concrete, intuitive and practically relevant method to quantify these differences is still lacking. Previous research, investigating differences between parallelly skidded and carved turns, relied on single variables such as joint angles and forces or muscle activities (Klous et al., 2012; Müller, 1994), that are difficult to illustrate for a coaching feedback and cannot necessarily put into practice directly.
Therefore, the aim of the current study is to conduct a more comprehensive and practice-oriented technique analysis between parallel skiing and carving by utilizing newly established data-driven technique metrics, that have been designed to align with observable technique elements (e.g. straight inward lean, backward lean, inward rotation of the upper body). As stated in the skiing curricula, it is hypothesized that carving is linked to increased backward lean and reduced upper body rotation. In addition, stability of the technique element executions, as a potential prerequisite to prevent falls, is investigated through the normalized jerk score (Hogan & Sternad, 2009). It is hypothesized that the carving motion is more stable, i.e. smoother and less jerky in its technical executions, than the parallel skiing motion due the absence of a side-skidding part and a larger supporting area between the skis.

METHODS: In the current study, 20 highly experienced skiers (8 female, 12 male; *M* = 26.0 years, *SD* = 4.5) with an active instructor license certified by the national ski federations of Austria or Germany were recruited. Each skier was instructed to perform the following trials for both the *parallel* and the *carving* turn techniques:

1. *Regular* turn technique as taught in the curriculum and demonstrated in skiing schools.

2. Turns with extremely pronounced *straight inward lean*.
3. Turns with extremely pronounced *backward lean*.
4. Turns with extremely pronounced *inward rotation* of the upper body.

Skiers were directed to maintain consistently long turn radii and execute movements as smoothly as possible. The order of the trials was randomized.

Three-dimensional movement data was collected using a wearable sensor system (Xsens™ Link, Movella Technologies, Enschede, NL) of hardware (17 IMUs located at prescribed positions of the whole body and attached by Velcro straps within a tight suit) and software (sensor fusion algorithms to obtain position data of 23 segments).

Skiing-specific technique metrics were derived from the data using PCA procedures, as detailed in a proof-of-concept study (Debertin et al., 2022). For each trial and participant, the procedure included: (i) data segmentation into two cycles, with one cycle defined as a combination of a left and right turn, (ii) data transformation into a skier-fixed reference frame, which moves and inclines with the skier into the turn (origin at the midpoint of the feet, x-axis in ski direction, y-axis as normal vector to a plane spanned by x-axis and the pelvis, z-axis orthogonally), (iii) centering around the skier's mean of the regular parallel and carving turn trial, (iv) body size-normalization by the timestep mean Euclidean distance from all coordinates. The PCA separates the original movement data (x,y,z-coordinates of 23 segments = 69 dimensions) from all trials and participants together into different "principal components" (PCs) by mathematically identifying directions of greatest variability in the dataset (Federolf et al., 2014). The variance induced by the extreme trials guided the PCs toward the encompassed movement patterns, i.e. some PCs actually uncover a movement from the regular position into the direction of the extreme and as a result provide quantitative metrics for the technique elements specified in the hypotheses (stick figure representations and PC score waveforms in Figure 1). Movement stability was quantified through the *normalized jerk score* (Hogan & Sternad, 2009) calculated for each PC score waveform.

Differences in waveforms were determined via statistical parametric mapping (SPM). Differences in stability were examined by paired t-tests (or Wilcoxon signed-rank tests for non-normally distributed data). The level of significance was set at $\alpha = 0.05$.

RESULTS: Within the first component (Figure 1a), only lateral movement is evident, indicating either an angulation of the hip (where the upper body shifts to the right during a left turn, and vice versa for a right turn) or a straighter longitudinal axis of the body. The PC score waveforms of regular parallel and carving trials differ within 12% of the entire cycle, significantly (SPM) only around turn transition. In this phase of the cycle, carving is characterized by a higher angulation of the hip. The inward lean instruction is clearly discernible in the regular trial (parallel) and slightly so in the carving trial. Lower normalized jerk scores indicate that this movement component is significantly more stable for carving compared to parallel skiing ($t(19) = 5.7$, $p < .001$), and higher for regular trials compared to extreme trials.

The second component involves a horizontal movement, that naturally implies a vertical proportion due to the slope gradient (Figure 1b). Carving occurs on significantly lower PC score scales, signifying a more posterior and lower body position. This difference is significant (SPM) throughout 86% of the entire cycle. In both techniques, a turn transition is initiated by a forward-upward motion, with carving reaching its maximum earlier. Explicit backward-leaning is discernible from the regular guideline-oriented techniques, with greater differences observed for parallel skiing tasks. Again, motion stability is higher in carving ($Z = 209$, $p < .001$).

Upper body rotational movement is observed in the fourth component (Figure 1c). The parallel and carving techniques exhibit significant differences (SPM) for 72% of the cycle. In the extreme forms, PC scores indicate inward rotation (upper body rotating into the turn direction) for positive values during a left turn and negative values during a right turn. The parallel technique is associated with outward rotation (upper body rotating to the left during a right turn), whereas carving skiers slightly rotated inwards during the steering phase and returned to a neutral orientation during the turn initiation phase. The upper body rotation motion was again more stable in carving as compared to parallel turning ($t(19) = 4.9$, $p < .001$).

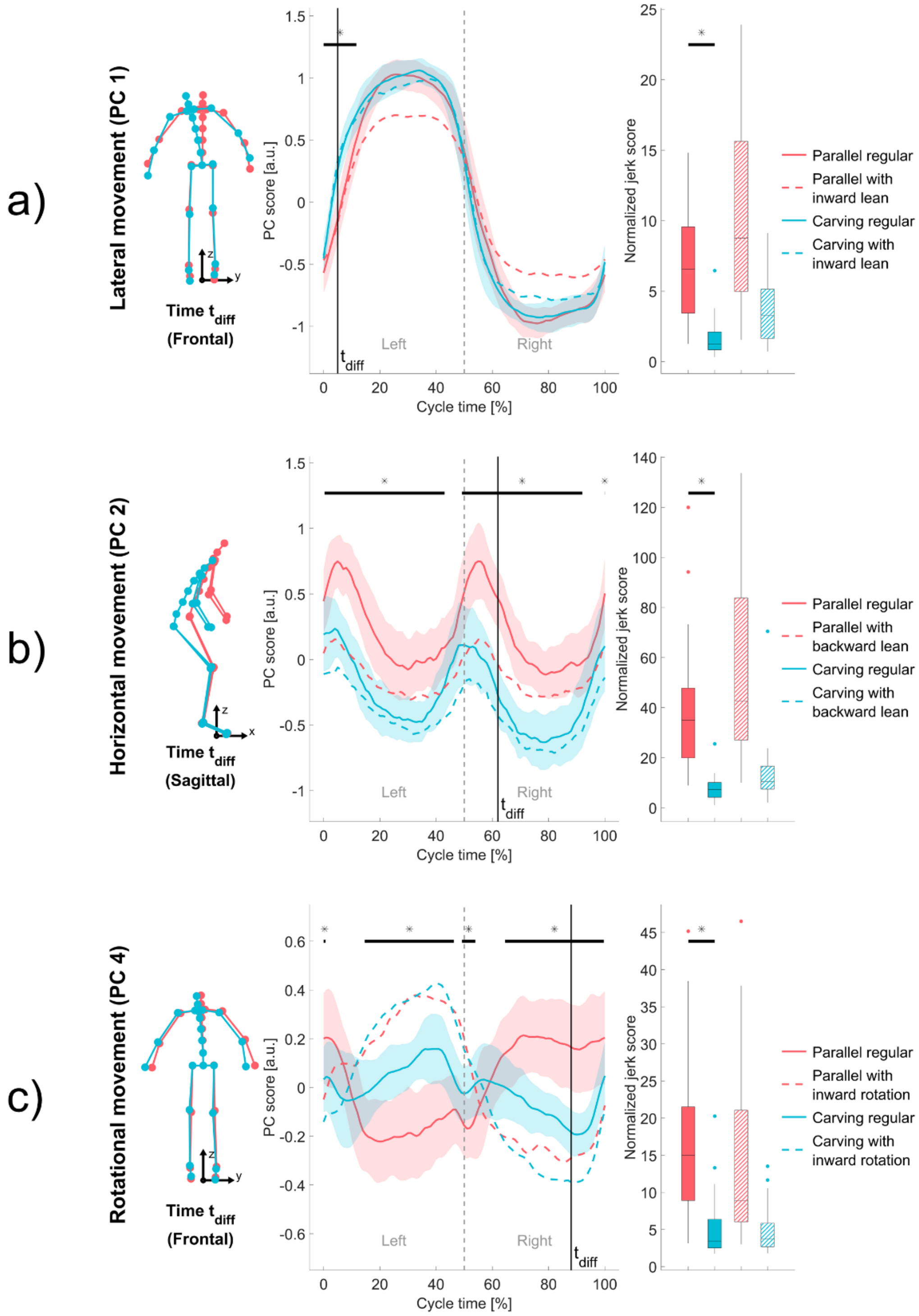

Figure 1: Comparison of "regular" guideline-oriented parallel (red) and carving (blue) turns based on the technique metrics for a) lateral; b) horizontal; and c) rotational movements of the upper body obtained from principal components (PCs). For the means of experienced skiers (n=20), the body configuration at the time of greatest difference (t_{diff}); PC score waveforms (bold lines with standard deviation areas) over a whole skiing cycle (left and right turn); and the normalized jerk scores are shown from left to right per PC. Additionally, results for the respective instructed extreme forms are plotted in dashed lines. Statistically significant differences (SPM, paired t-tests, Wilcoxon) between regular carving and parallel turns are marked by asterisks (*).

DISCUSSION: Applying PCA on practical data from expert skiers provided technique metrics through which the hypothesized technique differences between carving and parallel turns could be confirmed. The technique metrics represent quantifiable movements, aligning with body

configurations observable and directly interpretable by coaches or instructors. Carving showed a slightly more pronounced hip angulation, significantly higher backward lean, and reduced upper body rotation compared to the parallel turn technique. These findings align with the underlying guidelines (Austrian Ski School Association, 2015; German Ski Instructors Association, 2019). The higher hip angulation in carving may be attributed to a steeper and earlier incline into the turn, necessitating this movement action to shift the center of mass towards the skis.
Trials with consciously executed extreme inward lean, backward lean, and inward rotation can be visually differentiated (via stick figures) and quantitatively (via PC score values) from regular trials. Greater distinctions were observed for the parallel technique. This suggests that movement variations are relatively easier to execute within parallel ski steering, in turn suggesting that parallel skiing allows for more adaptability and flexibility. Conversely, varying movements while carving seems more challenging, suggesting that this technique presents fewer “affordances”, limiting the range of potential actions for the skier.
Movement executions were substantially more stable in carved than in parallel turns. The most probable source of instabilities in parallel turns is the side-skidding ski-snow interaction. Besides, carving is associated with increased speed (Müller et al., 2005) and a lower center of mass, which might also have a stabilizing effect on motion jerkiness.

CONCLUSION: The study quantitatively confirmed the hypothesized differences between parallel skiing and carving, aligning with the long-standing practical experiences that have culminated in the ski instruction curricula. This quantitative analysis of skiing technique elements also enabled the examination of secondary variables, such as motion stability. Specifically, the current study found substantially increased non-smoothness in parallel turning compared to carving, which was attributed to the mode of ski-snow interaction. In the future, the established technique metrics might be practically applied by both practitioners and researchers to link technical movements to performance outcomes and fall-related stability.

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ACKNOWLEDGEMENTS: The authors would like to thank all participants dedicating their time and efforts to the study and the “Tyrolean science funding” financially supporting this research.