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Task Experience Influences Coordinative Structures and Performance Variables in Learning a Slalom Ski-simulator Task

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Abstract

The experiment investigated the progressions of the qualitative and quantitative changes in the movement dynamics of learning the ski-simulator as a function of prior related task experience. The focus was the differential time scales of change in the candidate collective variable, neuro-muscular synergies, joint motions and task outcome as a function of learning over 7 days of practice. Half of the novice participants revealed in day 1 a transition of in-phase to anti-phase coupling of center of mass (CoM) - platform motion whereas the remaining novices and experienced group all produced on the first trial an anti-phase CoM-platform coupling. The experienced group also had initially greater amplitude and velocity of platform motion – a performance advantage over the novice group that was reduced but not eliminated with 7 days of practice. The novice participants who had an in-phase CoM-platform coupling on the initial trials of day 1 also showed the most restricted platform motion in those trials. Prior related practice experience differentially influenced the learning of the task as evidenced by both the qualitative organization and quantitative motion properties of the individual degrees of freedom (*dof*) to meet the task demands. The findings provide further evidence to the proposition that CoM-platform coupling is a candidate collective variable in the ski-simulator task that provides organization and boundary conditions to the motions of the individual joint *dof* and their couplings.

1. Introduction

Bernstein [1] postulated that learning was in essence, the mastery of the redundant degrees of freedom (*dof*) in joint coordination dynamics as a function of practice. He conceptualized that a novice performer learned to coordinate and control a large number of mechanical *dof* while attempting to learn a novel motor task. Bernstein proposed that novices would to the degree necessary freeze out the *dof* (joint angles) at the initial learning stage – an hypothesis that has been experimentally supported in the motions of arm segments in pistol shooting [2] and torso and leg motions in the ski-simulator task [3], although the particular order to freezing and freeing (releasing) of the joint motion appears strongly task dependent.

In the ski-simulator dynamic balance task, however, freezing the joint angles to project the CoM of the body vertically over the platform tends to result in an in-phase (upright standing posture-like) coupling between CoM and the platform, a kinematic relation that *limits* the range of lateral motion of the platform. Indeed, the in-phase macroscopic coordination relation is relatively unstable on the platform and cannot realize the task goal of large, fluid and efficient platform movement (amplitude and velocity) as reflected in a skilled ski-simulator performance. Thus, the macroscopic CoM – platform coupling sets boundary conditions on the platform motion as determined in the task space of its amplitude and velocity [9,10].

The CoM and platform relative motion reflects an emergent property of the qualitative and quantitative movement dynamics that we examine here in the progressions of learning the dynamic balance ski-simulator task as a function of prior related task experience. A primary question was whether the macroscopic phase transition of the CoM – platform motion occurs only after considerable practice and a change in the intrinsic dynamics as found in learning the roller ball task [4] or whether it occurs following limited practice as a consequence of familiarization and 'getting the idea' of the task [5–7]. The latter concept of 'getting the idea' has been long held to occur in the early stage of motor skill learning but typically it has not been studied directly in terms of qualitative movement kinematics. Qualitative is used in the context of a different nominal macroscopic movement pattern such as in-phase and anti-phase of CoM to platform.

Here we examine this feature of learning in terms of the presence and/or change of the macroscopic movement dynamics as a function of learning. The proposition to be investigated is that a qualitative variable such as CoM-Platform in-phase relative motion constrains the organization of the joint and synergy motions and thus the learning of the ski-simulator task requires an anti-phase pattern to its organization for successful performance. Getting this macroscopic organization in the movement dynamics can be viewed as the dynamical essence of 'getting the idea' of the task. Moreover, a rapid time scale of change of the CoM - platform phase relation would support the interpretation that both the in- and anti-phase CoM-platform dynamics are relatively stable states of the dynamics as in the HKB model for bimanual control [8].

The proposition that CoM-platform coupling may be a candidate collective variable in the whole body ski-simulator task has experimental rationale. That CoM is a property of the macroscopic variable follows from it being a spatial point where the body mass is distributed equally in all directions thus making it fundamental to postural balance tasks [9]. It is also consistent with the evidence for CoM-CoP as the candidate collective variable in experimental investigations of standing posture [10] and an externally driven dynamic platform balance protocol [11]. An important consequence of the several joint space degrees of freedom in whole-body dynamic balance tasks is that they allow in principle, unlike the restricted 2 *dof* bimanual coordination task [8], the independent consideration of the motion of a macroscopic variable from that of particular neuro-muscular joint synergies (couplings) and individual joints. This broader range of variables in the task dynamics allows a test of the notion of reciprocal causality of the organization of the macroscopic variable with the individual joint motion and synergies[11]. Thus, the ski-simulator task with many joint *dof* motions involved affords a rich context for movement dynamics and the study of the rates of change of the motions of candidate collective variable, neuro-muscular synergies, individual joints and platform as a function of prior practice experience and days of practice in the ski task.

In coordination dynamics [12], the changes in movement dynamics with learning are embedded within the formation of the collective variable through reciprocal causality with the individual *dof* joint motions and couplings of varying relations, strengths and time scales between the multiple *dof* – adjoining phase relations in joint space [13–16]. Indeed, Bernstein[1] proposed that the three stages of learning a novel skill involve – freezing out mechanical *dof* of joints, gradually releasing the constrained *dof* and finally exploiting (taking advantage of) the reactive forces of the motions of the *dof* to produce economical and efficient movement as a function of practice. This pathway of change in motor learning eventually leads to fluent, rhythmical and large amplitude movement in the ski-simulator task [3,17], including potentially an anti-phase coupling of CoM-platform motion that is required (albeit implicitly) to realize the task demands [14].

In this study we examined the hypothesis that the time scales of change in forming the respective couplings would be different for the macroscopic variable (CoM-platform motion) than the neuro-muscular synergy variables as a function of the control parameter that is, the increasing platform amplitude and velocity motion that emerges with practice [13,14]. It was anticipated that if the anti-phase collective variable was not produced in the initial trials of practice it would emerge from a transition at some point in practice to an anti-phase pattern. In contrast, the synergy variables would reflect transient and faster time scale change with different relative phase values than the candidate collective variable over the progression of practice.

Furthermore, it was hypothesized that the participants experienced in task related activities would produce an earlier and more distinct anti-phase coupling than the novice participants even though they had not practiced the specific lateral motion ski-simulator task studied here. This is consistent the proposition that the intrinsic dynamics provide boundary conditions to the organization movement of coordination and control and the change of it in learning, retention and transfer[11]. The time of acquisition of a new bimanual relative phase has been shown to be dependent on the prior experience of the learners [18,19], including in the context of sports skills [20–22]

In general, it was expected that, that the rate of freeing the individual joint *dof* across practice days would be different as a function of prior practice and task experience, and that this would be influenced by the phase relation of the macroscopic CoM-platform motion. The novice group would initially produce a more progressive rate of increment of lower limb joint angle range (freeing *dof*) than the experienced group because initially in practice they would have a more restricted platform amplitude through reduced ankle, knee, and hip joint motion. And, to realize this change, the novice group would produce a higher variability of lower limb joint angle motion as a function of practice (exploiting *dof*) given that they had more change in platform motion to realize the task goal from their limited initial posture and movement conditions.

The rates of change of the motion of the candidate collective variable, synergies, individual joints and platform would be different as a function of prior practice experience and days of practice in the ski task. The qualitative and quantitative changes in the movement dynamics would show properties of both the continuity and discontinuity of motor skill learning [23–26], that depend on prior practice experience.

2. Methods

Participants

Twelve healthy female participants (23 ± 5 years) were recruited according to an experimental protocol approved by The Pennsylvania State University Institutional Review Board. The participants consisted of two groups – novice and experienced skiers. The novice group had no previous experience of dynamic balancing tasks such as surfing, skiing, rollerblading and snowboarding, whereas the experienced group consisted of experienced alpine skiers (> 5 years of skiing) from a local ski club team. None of the participants from either group had any previous practice experience on the ski-simulator task studied here. Their average height was 164.4 ± 6.2 cm and their average mass was 53.2 ± 4.3 kg. There was no average group difference in height/mass. All participants self-reported no apparent neurological disorders or musculoskeletal injuries that could negatively influence postural control.

Apparatus

The ski-simulator (Skier's Edge, Utah) was the experimental apparatus that is a movable wheeled platform comprising of two co-dependent footplates [3]. The elastic band fitted underneath the footplates facilitates lateral oscillations. A six-camera 3-D motion analysis system (QTM, Sweden) was positioned with the cameras equally distant from each other around 360° of the participant to encompass the calibrated space of the test area and record the motion of passive markers that were attached to the anatomical joints of the experimental participants. The data were sampled at 100 Hz and were digitally low-pass filtered with a second order Butterworth filter and a cut-off frequency of 5 Hz. An initial assessment to determine the frequency power of the dependent variables was carried out by running an FFT. It was found that the signal power was constrained to <2 Hz for all signals and subsequently analyzed consistent with an earlier study [13].

Task and Procedures

The participant's task instruction was to make as large an amplitude and velocity side-to-side movements on the ski-simulator as they could with their hands folded in the front of their torso. No additional information was provided. Each participant practiced for 140 trials spanning over 7 consecutive days. Every trial consisted of 45 s of practice followed by 1 min of rest.

Data Analysis

***Kinematic variables**:* The kinematic variables were the individual joint angles (hip, knee and ankle) calculated in the mediolateral (ML) axis that were defined based on passive markers attached to anatomical landmarks. The CoM was calculated from the 13 segment model, reconstructed from a 20 anatomical marker system - lateral side of head, shoulder (lesser tubercle of humerus), wrist (radial styloid process), elbow (lateral epicondyle of humerus), iliac (tubercle crest), hip (greater trochanter), knee (lateral femoral epicondyle), ankle (frontal talus), toe (3rd metatarsal) according to the anthropometric data of Dempster [27]. Applying the weighting factors of the segmental masses, the whole body CoM position was estimated by the weighted summation of the individual segment CoM positions [9].

***Cophase**:* The coupled variables of CoM-platform, head-platform, hip-ankle, hip-knee and knee-ankle were investigated through the cophase technique [28]. For kinematic data analysis, we considered the right ipsilateral joints. Here, 0° implies that the signals are coupled and in-phase, whereas anti-phase mode would be reflected by +180°.

$$Cophase(f) = atan2d[-imag(S_{ab}(f)), real(S_{ab}(f))] \qquad (1)$$

where $S_{ab}(f)$ is the cross power spectral density of the two time-series [29].

The cophase characterizes the lead-lag relation of two signals as a function of frequency. For example, a 0° cophase indicates an in-phase coupling that two time-series simultaneously travel together. On the contrary, a 180° cophase represents an anti-phase coordination that one signal has a half cycle delay to the other (e.g., -180° implies that signal *y* leads *x*). More precisely, if the phase difference is stable and constant over time i.e., phase locked then coherence=1.0 and if time difference between two signals varies from moment-to-moment then coherence=0. The descriptive circular statistics (mean and SD) were derived to reveal the cophase patterns for all articular couplings and the CoM-platform coordination qualitatively [30]

Coherence: The coupled variables were analyzed using the Chronux toolbox [31]. Coherence measures the correlation of two signals in the frequency domain where multi-taper spectral tool reduces the spectrum estimation bias by obtaining multiple independent estimates from the time-series that are dependent on the sampling frequency and time-series bandwidth [32]. Typically, values range between 1 (perfect linear prediction between variables) to 0 (variables are linearly independent).

$$Coherence(f)^2 = \frac{|(S_{ab}(f)|^2}{S_a(f).S_b(f)} \qquad (2)$$

where $S_a(f)$ and $S_b(f)$ are the power spectral densities of signal *a* and *b*, respectively.

Statistics*:* A two-way mixed design repeated measures ANOVA of 7 (days) x 2 (groups – novice and experienced) was carried out independently on the CoM-platform, head-platform, hip-ankle, hip-knee and knee-ankle couplings, individual joint angle variables and platform kinematics. The Tukey post hoc test was used to determine the differences between all paired levels for the dependent variables. Circular statistics was used to calculate the mean and standard deviation of coherence across the trial period [30]. Alpha level was set $p < .05$.

3. Results

Platform Kinematics

The amplitude of the lateral skiing movement for the novice group increased significantly as a function of practice days and more than the experienced group (see Figure 1), but the experienced group still produced a greater range of platform motion than the novice group on day 7. The amplitude of platform motion of the novice group was 16.36 ± 4.26 cm ($n = 6$) on day 1 which increased to 37.32 ± 1.56 cm on day 7. In contrast, the experienced group had a mean of 35.91 ± 1.51 cm on day 1 that increased to 40.45 ± 1.05 cm on day 7.

A repeated measures ANOVA with days (7) and groups (2: novice and experienced) on platform amplitude showed a significant main effect of group, $F(1, 70) = 21.62$, $p < 0.05$; day, $F(6, 70) = 236.34$, $p < 0.05$, and a significant interaction between groups and days, $F(6, 70) = 10.34$, $p < 0.05$. The Tukey post-hoc test showed that all pairwise comparisons of the interaction were significant.

[Insert Figure 1 about here]

A repeated measures ANOVA with days (7) and groups (2: novice and experienced) on platform frequency showed a significant main effect of group, $F(1, 70) = 10.07$, $p < 0.05$; day, $F(6, 70) = 46.37$, $p = 0.05$, and a significant interaction between groups and days, $F(6, 70) = 55.90$, $p < 0.05$. The Tukey post-hoc test showed that all pairwise comparisons were significant although the direction of initial group difference was reversed in days 3-7.

For platform velocity the main effect of group was significant, $F(1, 70) = 489.01$, $p < 0.05$, and there was a significant interaction of group and day, $F(6, 70) = 201.24$ at $p < 0.05$. The Tukey post-hoc test showed that all pairwise comparisons were significant.

[Insert Figure 2 about here]

Figures 2a and 2b depict example time series of platform, CoM and head motion early and late in practice for a novice participant who showed a phase transition of CoM-platform motion. The ML motion kinematics of CoM, Head and Platform showed an in-phase CoM-platform motion on day 1, trial 1 and subsequent performance with an anti-phase CoM-platform motion on day 7, trial 20, respectively. On day 1, trial 1, the amplitude of the platform motion was highly constrained (~ 1 cm) with a low CoM oscillating amplitude (~2 cm) and a relatively large head oscillating amplitude (~7 cm), reflecting an inverted pendulum motion, i.e. larger amplitude in the distal end (e.g., head) and constrained amplitude at the pivoted end (e.g., platform). In contrast, for the same participant on day 7, trial 20, the oscillating amplitude of the platform was larger (~ 17 cm), whereas the amplitude of CoM oscillated intermediately (~ 5 cm), and the amplitude of head oscillation was highly conserved (~ 3 cm), reflecting a hanging pendulum and an anti-phase CoM-platform mode.

Figure 2c reflects the platform amplitude for the first three trials on day 1. The bold line plot represents the group mean of the novice participants, whereas the dotted line plot depicts the subset of three novice participants who did not demonstrate an anti-phase coupling of CoM and platform in the initial stage of practice. The platform amplitude appears to have a relation with the cophase values among the three novices as shown and discussed later in Figure 2d.

Joint Angle Properties

[Insert Table 1 and Figure 3 about here]

Figure 3 and Table 1 depict the mean and *SD* of joint angle motions - ankle, knee and hip - for the two groups, calculated over joint angles from both sides of the body as a function of practice days. Clearly, the novices enhanced substantially their joint angle range across practice days for ankle, knee and hip motions (see Figure 3). The novices also increased their relative standard deviation (CV%) for all lower joint angles over practice days (see Table 1), that was reflected by a larger change in percentage of coefficient of variation. The experienced group essentially maintained their respective joint angle standard deviations across practice days.

A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the knee joint angle range showed significance for group, $F(1, 70) = 21.07$, $p < 0.05$. A similar analysis on hip joint angle range also showed significance for the main effect of group, $F(1, 70)$

= 13.17, $p < 0.05$. There was neither a main effect for days nor an interaction between groups and days.

A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the knee angle showed a main effect of group, $F(1, 70) = 50.16$, $p < 0.05$, where the experienced group had larger joint angle motions than the novice group. Similarly, there was a main effect of group for the hip angle, $F(1, 70) = 50$, $p < 0.05$, where the experienced group had larger joint angle motions than the novice group. A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the standard deviation of ankle joint angle showed a significant main effect of group, $F(1, 70) = 234.84$, $p < 0.05$. For knee joint angle and hip joint angle standard deviation, the main effect of group was also significant, $F(1, 70) = 102.71$, $p < 0.05$ and $F(1, 70) = 236.57$, $p < 0.05$, respectively.

Cophase

Figure 3d illustrates the cophase values of the CoM-platform coupling for each individual novice participant on day 1 across trials 1 to 3. Two novice individuals in the study, transitioned from in-phase coupling (~0º) to anti-phase coupling (~180°) between trial 1 and trial 2. One novice individual transitioned from in-phase to anti-phase coupling between trial 1 and trial 3, whereas the remaining novices and all the experienced participants showed anti-phase CoM-platform coupling on the initial trial of day 1.

[Insert Figure 4 about here]

Figure 4 illustrates the cophase on the different couplings (CoM-platform, head-platform, hip-ankle, hip-knee and knee-ankle) across practice days for the two groups – experienced (left panel) and novice (right panel). The CoM-platform cophase values were around 174° for the experienced (ex) and 161º for the novice (no). Similarly, the two groups showed a difference in head-platform coupling, 155º (ex) and 135° (no), respectively. Regarding the joint motions, the mean cophase values were 77° (ex) and 76º (no) for hip-ankle, 46° (ex) and 40º (no) for hip-knee and 55º (ex) and 57° (no) for knee-ankle.

A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the cophase values of CoM-platform showed a significant main effect of group, $F(1, 70) = 231.24$, $p < 0.05$. Similarly, for head-platform cophase values the group main effect was significant, $F(1, 70) = 43.69$, $p < 0.05$. Although the main effects of days and groups were non-significant for the hip-ankle cophase values (dependent variable), there was a significant interaction of group and days, $F(6, 70) = 2.19$, $p < 0.05$. A post hoc Tukey test showed that for the variable of hip-ankle cophase, the values increased with practice in the experienced but not in the novice group, with groups differing significantly at $p < 0.05$. For hip-knee cophase values the main effect of group was significant, $F(1, 70) = 43.6$, $p < 0.05$.

Coherence

[Insert Figure 5 about here]

Figure 5 illustrates the coherence with *SD* of the different couplings of CoM-platfom, head-platform for experienced (upper left panel), hip-ankle, hip-knee and knee-ankle for experienced (upper right panel), CoM-platfom, head-platform for novice (lower left panel) and hip-ankle, hip-knee and knee-ankle for novice (lower right panel). A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the coherence values of CoM-platform showed a significant main effect of group, $F(1, 70) = 241.26$, $p < 0.05$. Similarly, for head-platform coherence values the group main effect was significant, $F(1, 70) = 44.37$, $p < 0.05$. The interaction of group and days, $F(6, 70) = 2.23$, $p = 0.05$ was significant for hip-ankle coherence. A Tukey-Kramer post-hoc showed an interaction of group experience and day 5, $p = 0.05$. Tukey post-hoc test showed that coherence of the experienced group was greater than the novice group.

4. Discussion

The study investigated the acquisition of a dynamic postural balance task (ski-simulator) as a function of prior practice experience in a related whole-body motor task (downhill skiing). The theoretical and operational focus was to investigate if there were differential qualitative and quantitative pathways of change in the candidate collective variable (CoM-platform), joint synergies, individual joint motions and task outcome of this multiple *dof* task as a function of prior practice experience. We examined if these categories of system variables have differential time scales of change, relations and functional roles of influence in the evolving organization of the *dof* and task outcome as has been proposed in dynamical systems approaches to motor skill acquisition [1,12,23,33].

Task outcome. The platform frequency, amplitude and velocity were analysed to investigate the change in task outcome as a function prior practice experience and actual practice on the ski-simulator [3,34,35]. The two groups clearly showed different pathways of continuous change in task outcome over practice [36,37], and this was most evident in progressions of platform amplitude and velocity. The novice group had very limited platform motion on the initial trials of day 1, particularly in the early trials of the participants showing an in-phase CoM – platform motion, but they progressively increased the amplitude range of motion and average velocity of the platform over the 7 days.

After the initial trials of Day 1, the platform frequency remained relatively constant (change < .10%) over practice days for both groups whereas the novice group increased amplitude and average velocity by more than 100%. Indeed, it seems that the learning strategy for both groups once they became ‘familiarized’ or ‘got the idea’ of the task [5,38] was to increase platform amplitude and average velocity while essentially preserving a modal frequency of the anti-phase CoM-platform motion. Thus, both the phase-relation and frequency of CoM-platform motion are providing an organizational structure of the macroscopic dynamics in this ski-simulator task. The relatively stable modal frequency after initial practice is consistent with the proposition that this variable is driving the efficiency of the movement ski-simulator.

We anticipate that further practice would reduce and eventually eliminate the performance difference between the groups [39]. Nevertheless, the re-organization of the release of the *dof* by the novice group seems on a slower time scale in this whole body task than typically is found in the motor learning of upper limb movement scaling tasks [37]. This difference in the time scales of change in the kinematics reflects the different stages of learning realized by the novice and experienced groups. The slower rate of release of joint angle by the novices is also consistent with the proposal that the stability requirement (staying upright on the simulator) induces a more cautious search strategy in terms of increment of change in the movement kinematics [40].

The experienced group had practiced downhill skiing for many more hours than were practiced here in the lateral ski motion of the simulator, an experience that clearly induced a positive transfer to both the qualitative and quantitative movement dynamics of the laboratory ski analogue. An interesting theoretical and open experimental question that has practical ramifications is whether positive transfer also occurs from original practice on the ski-simulator to the actual activity of downhill skiing.

CoM-Platform relation. A central focus was an examination of Bernstein (1967) *dof* problem in the early stage of skill acquisition (freezing the redundant *dof*) and the subsequent stages of skill acquisition (including freeing the redundant *dof*). In an earlier study, evidence was shown for the phenomena of freezing and freeing *dof* as a function of practice in the ski-simulator task [3]. However, previous ski-simulator and acquisition of multiple *dof* coordination studies have not compared the pathways of change of individual joint motions and their couplings with the change of a candidate collective variable, together with how prior skill level influences such motor learning [13,16,39,41].

The findings showed that there were both qualitative (see Figure 2d) and quantitative (see Figure 4 & Figure 5) patterns of change as a function of practice time in learning the lateral skiing movement. Prior practice experience in a related task was found to influence the probability of producing on the initial trial an anti-phase mode to CoM-platform motion. All experienced skiers showed an anti-phase mode of CoM-platform on trial 1 that was performed consistently through the practice days whereas three (50%) novices showed a phase transition from an in-phase to anti-phase CoM-platform coordination mode between trial 1 and trial 3 on day 1. However, the three novices that transitioned the CoM-platform relative phase did so after, in effect, minimal practice. The relatively rapid transition with practice is consistent with the position that a relatively stable mode of anti-phase CoM-platform was available that required merely familiarization through preliminary practice in context to induce.

This finding on the rapid change in the qualitative movement dynamics is consistent what Fitts (1964) called ‘getting the idea’ of the task in motor learning. The rapid transition from in-phase to anti-phase for the subset of novice learners holds parallels with the experimental evidence from the HKB model for bimanual control [8]. In contrast, the learning of the rollerball task that has shown performance discontinuities with differential time scales of change across practice that reflects the freeing of *dof* at different stages of practice [4]. It appears that the time scale of forming a macroscopic variable for a coordination pattern in a novel motor task is likely to have considerable variation over participants and tasks.

The findings showed that as a function of practice the inverted pendulum mode of CoM-platform switched to a hanging pendulum mode with progressively large amplitude in the distal end (platform) and constrained amplitude at the pivoted end (head) to reflect the learning of a new anti-phase coordination pattern [3,16]. Only the anti-phase CoM-platform mode provides the biomechanical support to the freeing of the joint space *dof* and a larger amplitude and more rapid lateral oscillatory movement pattern. This reveals that the freezing and freeing of the individual joint space motions as articulated by Bernstein (1967) need to be considered in the context of the macroscopic organizing or collective variable for the task [11,12,42].

We interpret the transition in the CoM-platform coordination pattern to be consistent with the hypothesis of it being the collective variable for this task. The experiment did not test this proposition by scaling a movement property as a control variable as shown originally in the HKB model [8] of bimanual coordination and for an externally driven platform posture dynamic balance task [11]. Rather, here we had a self-generated motion by learners with different prior practice experience and actual practice acting as a control variable that influenced the formation and expression of the global variable of CoP-platform coupling and the differential scaling of the individual and synergetic joint motions.

The organization of the *dof* showed also that the CoM and head motions can reflect independent kinematic properties when compared from the first (day 1, trial 1) to the last phase of practice (day 7, trial 20) (see Figure 2a and Figure 2b). A subset of the novice participants adopted initially in practice an inverted pendulum mode with large amplitude in the distal end (head) and constrained amplitude at the pivoted end (platform) that was essentially in-phase. The CoM motion when compared to head motion as a function of increasing platform velocity reveals that CoM has a slower rate of change and was more stable as a function of the emergent control parameter (platform velocity). Thus, our findings show that head motion can become independent to some degree of the motion of the CoM given the confluence of constraints to movement in action [43] including the task demands [44].

Joint motion excursions and couplings. Prior practice experience significantly facilitated the release with practice of the excursion of motion at the individual joint (ankle, knee, and hip) *dof* but this only took place within the anti-phase CoM-platform mode. Thus, release of the individual *dof* and the increased excursion of joint motion were strongly influenced by prior practice experience and the adoption of the antiphase CoM-platform mode. We postulate that the relatively slower rate of change (release) in joint motion by novice learners over practice was due to the stability demands of the dynamic postural task and a conservative approach to the perceived negative consequences of the loss of balance on the ski-simulator.

The coherence values of the coupling of CoM, head, platform, hip, knee and ankle motion along ML direction revealed that the experienced group was already attuned to the demands of the ski-simulator task and hence executed anti-phase coupling of CoM-platform from trial 1, day 1 unlike 50% of the novice group. The coherence analysis showed that the coordination dynamics of the CoM-platform coupling had distinct coherence values (~1) when compared to the coupled synergy variables (~ <0.5) across practice days (see Figure 5) for both groups. The intermediate coherence values of synergy variables (hip-knee-ankle pairings) provide further evidence that the coupling of the synergies was on a different timescale from that of the candidate collective variable – a feature that can emerge in the multiple *dof* task [11]. Overall, for both groups, the coupling measures of coherence and cophase of the joint motions showed little persistent change over the 7 days of practice and little influence of prior practice experience, consistent with a reflection of a different functional role than that of the candidate collective variable and the regulation of the task outcome. Indeed, where a drift in mean value of the cophase or coherence for the synergies occurred the relative level of change was considerably smaller than the order of magnitude changes in the task outcome, individual joint motions and the CoM-platform relative phase (for those participants who showed the transition).

The multiple patterns of change in the different categories of variables over practice time reflect the flexibility and degeneracy of the system and the challenge of understanding change and learning in a nonlinear system with multiple *dof* [1]. Nevertheless, the findings revealed continuity in the incremental progression of task outcome (platform position and velocity) in both the novice and experienced groups in a way that is consistent with traditional findings of change in task outcome through motor learning [36,37]. This does not mean that the change in task outcome in motor learning is always continuous and progressive [4] or that the persistent change over practice time in the collective variable, individual joint motions or synergies will follow the differential patterns and time scales shown here.

Perspectives. The findings show that in learning this whole-body sports-related ski-simulator task prior experience and practice induce different rates of change in the categories of movement variables, including: task outcome, the candidate collective variable, neuromuscular synergies and joint motions. Traditional emphasis in motor skill learning has been on achieving the task outcome and to a lesser extent the role of the change in joint motions to realize this goal. Here, however, the functional role of the macroscopic variable of CoM-Platform motion (phase relation and frequency) is revealed in organizing the motions of the individual *dof* and joint motions. The release of the individual joint *dof* with practice [16] is dependent on the global organization of the movement system. The formation of the macroscopic movement dynamics through practice is an under researched problem of the early stage of skill learning previously described as getting the idea of the task [5,38]. The findings show the functional role of the integration of postural and limb motion dynamics in a sports-related task and provide a new direction of inquiry for the many existing instructional strategies of motor skill acquisition [45].

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Table 1. Group mean coefficient of variation (CV %) of experienced and novice groups of their joint (ankle, knee and hip) motions across practice days.

	Ankle Angle (CV %)		**Knee Angle (CV %)**		**Hip Angle (CV %)**	
Practice	**Experienced**	**Novice**	**Experienced**	**Novice**	**Experienced**	**Novice**
Day 1	7	30	5	16	4	10
Day 2	8	34	6	19	5	13
Day 3	7	37	6	22	5	15
Day 4	7	45	6	22	5	16
Day 5	6	43	6	25	5	17
Day 6	7	51	6	23	5	17
Day 7	7	53	6	24	5	17

Figure Legends

Figure 1. Group mean of platform frequency, amplitude, velocity (error bar between subjects' standard deviation) of lateral skiing movement as a function of experienced and novice groups across practice days.

Figure 2. Representative novice subject – (a) - day1, trial 1, (b) - day7, trial 20, (c) – platform amplitude for novice group and group average for day 1, trials 1-3, (d) cophase values of CoM-platform (ML plane) all novices for day 1, trials 1-3.

Figure 3. Group mean of joint angle range (ankle, knee and hip - error bar between subjects' standard deviation) of experienced and novice groups across practice days.

Figure 4. Group mean of cophase of pair-wise couplings of experienced and novice groups (error bar between subjects' standard deviation) across practice days.

Figure 5. Group mean (of coherence of pair-wise couplings of experienced and novice groups (error bar between subjects' standard deviation) across practice days.

Figure 1.

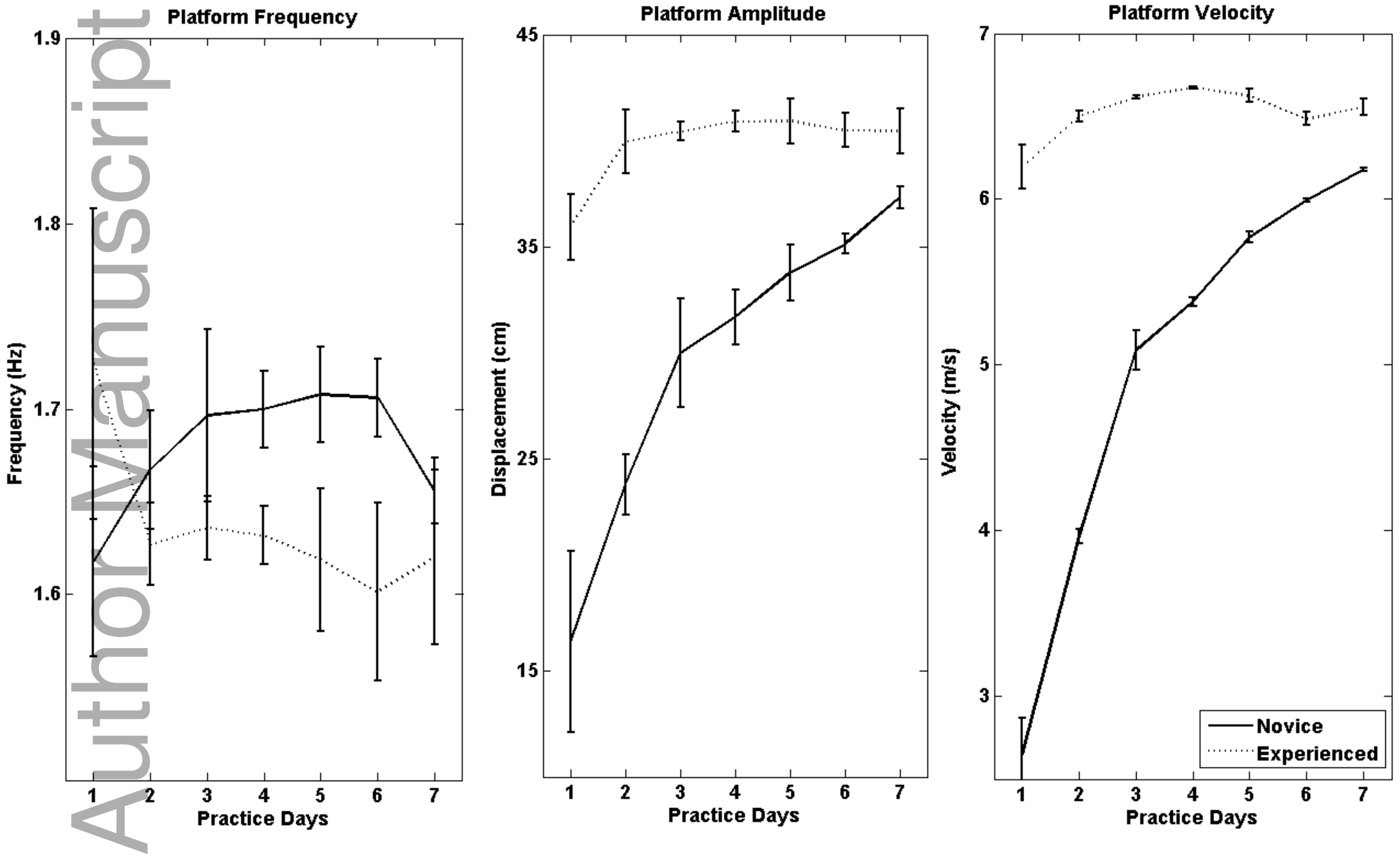

Platform Frequency
Frequency (Hz)
1.9
1.8
1.7
1.6
Practice Days
1
2
3
4
5
6
7
Platform Amplitude
Displacement (cm)
45
35
25
15
Practice Days
Platform Velocity
Velocity (m/s)
7
6
5
4
3
Practice Days
Novice
Experienced

Figure 2.

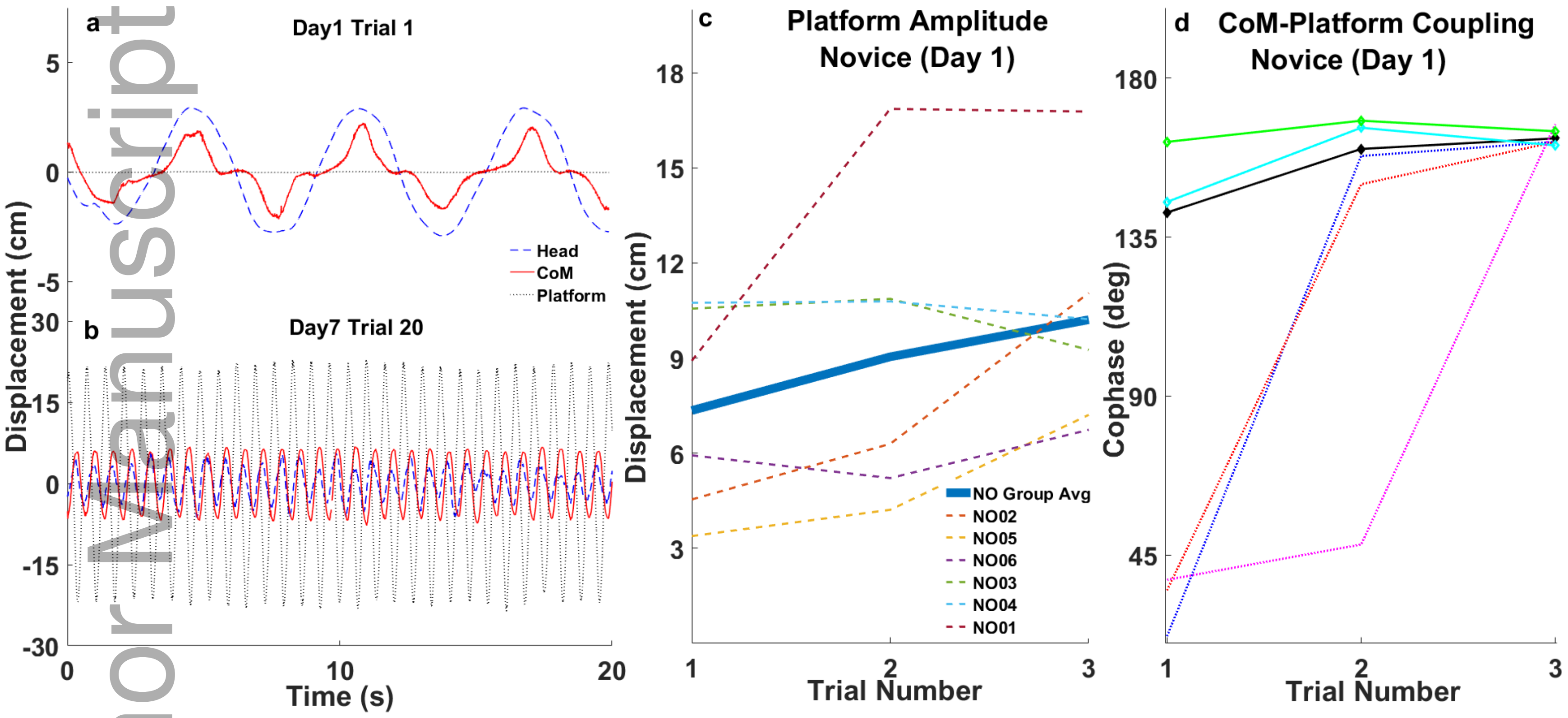

a
Day1 Trial 1
5
0
-5
Head
CoM
Platform
b
Day7 Trial 20
30
15
0
-15
-30
Displacement (cm)
0
10
20
Time (s)
c
Platform Amplitude
Novice (Day 1)
18
15
12
9
6
3
Displacement (cm)
NO Group Avg
NO02
NO05
NO06
NO03
NO04
NO01
1
2
3
Trial Number
d
CoM-Platform Coupling
Novice (Day 1)
180
135
90
45
Cophase (deg)
1
2
3
Trial Number

Figure 3.

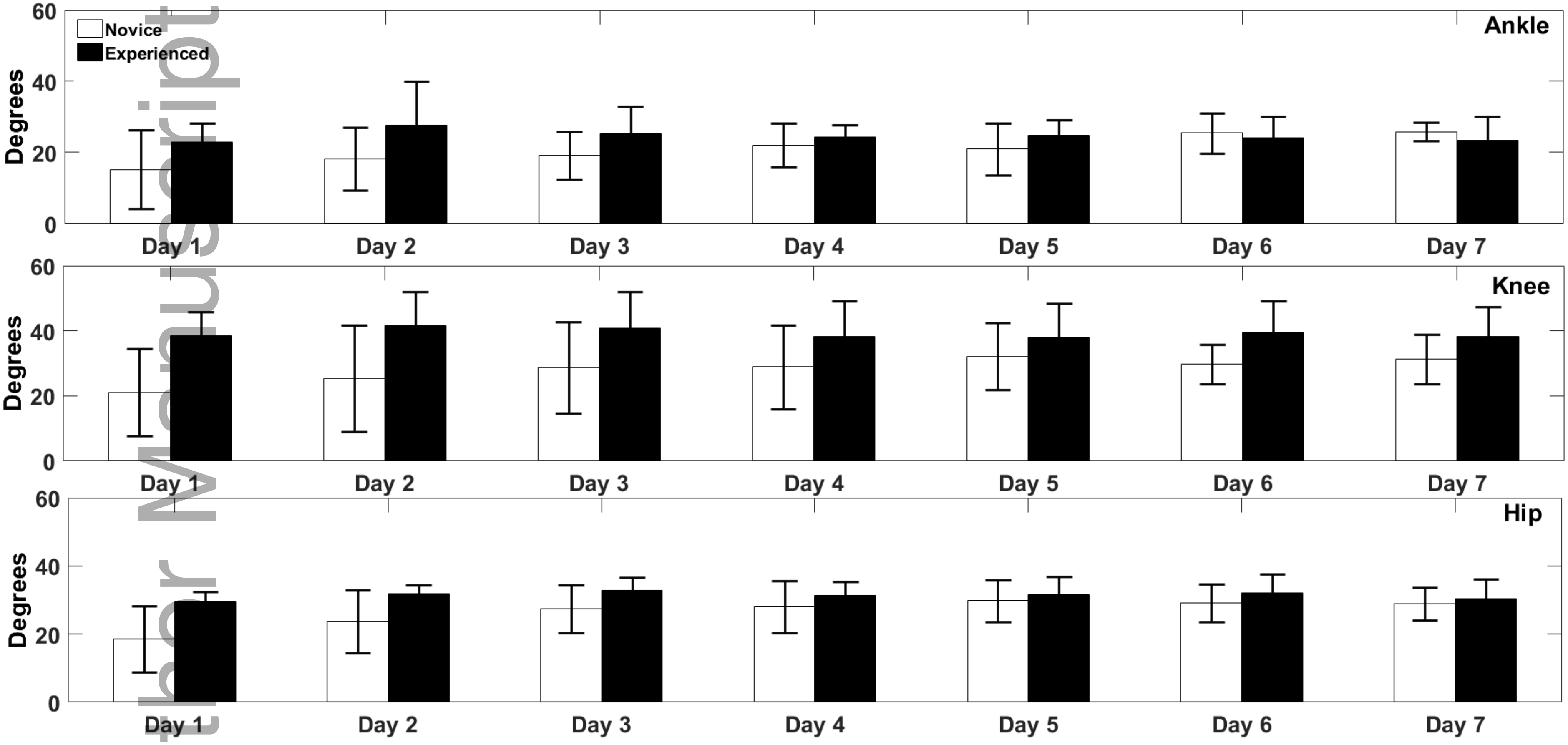

Novice
Experienced
Ankle
Knee
Hip
Degrees
60
40
20
0
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Day 7

Figure 4.

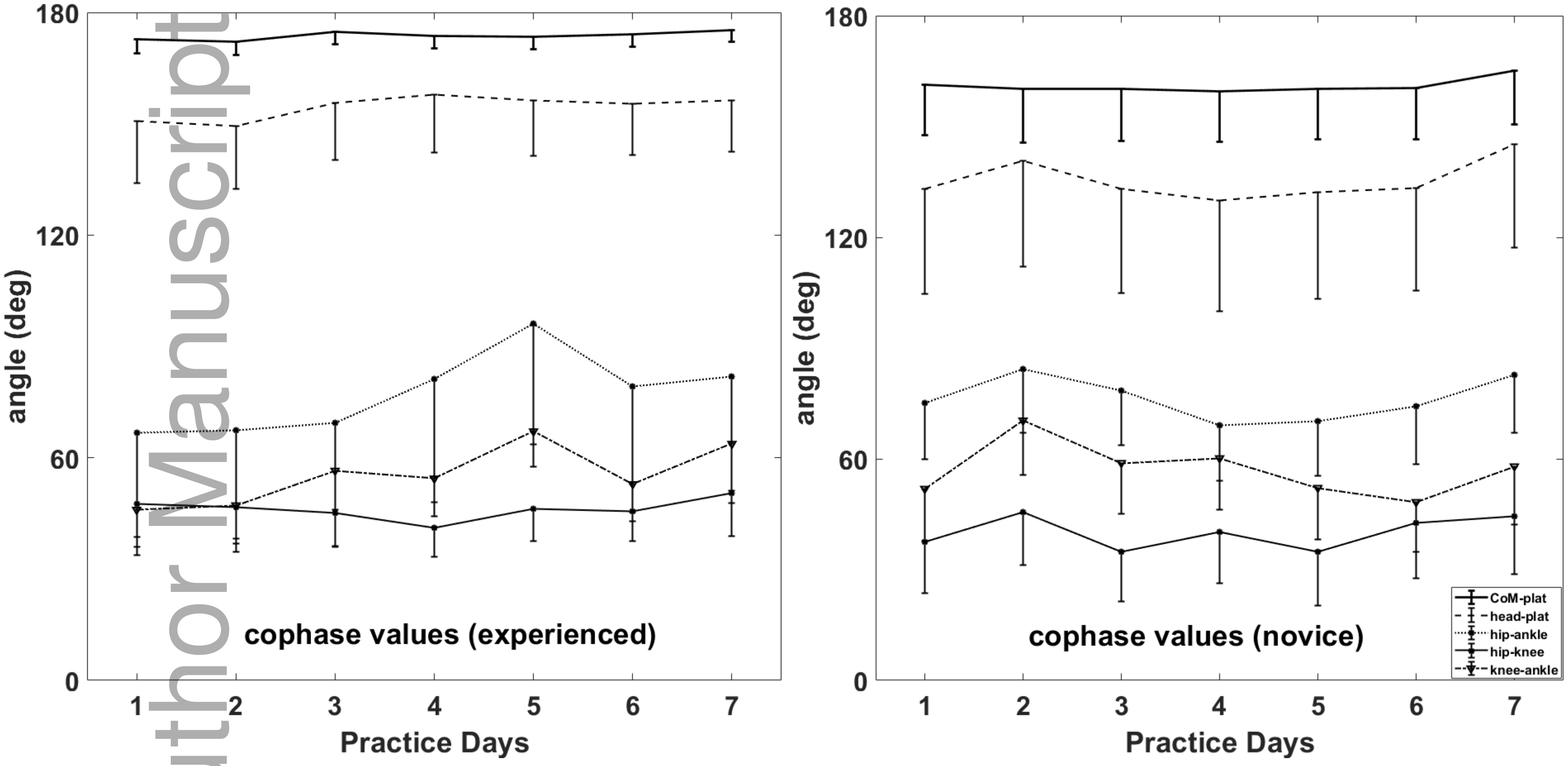
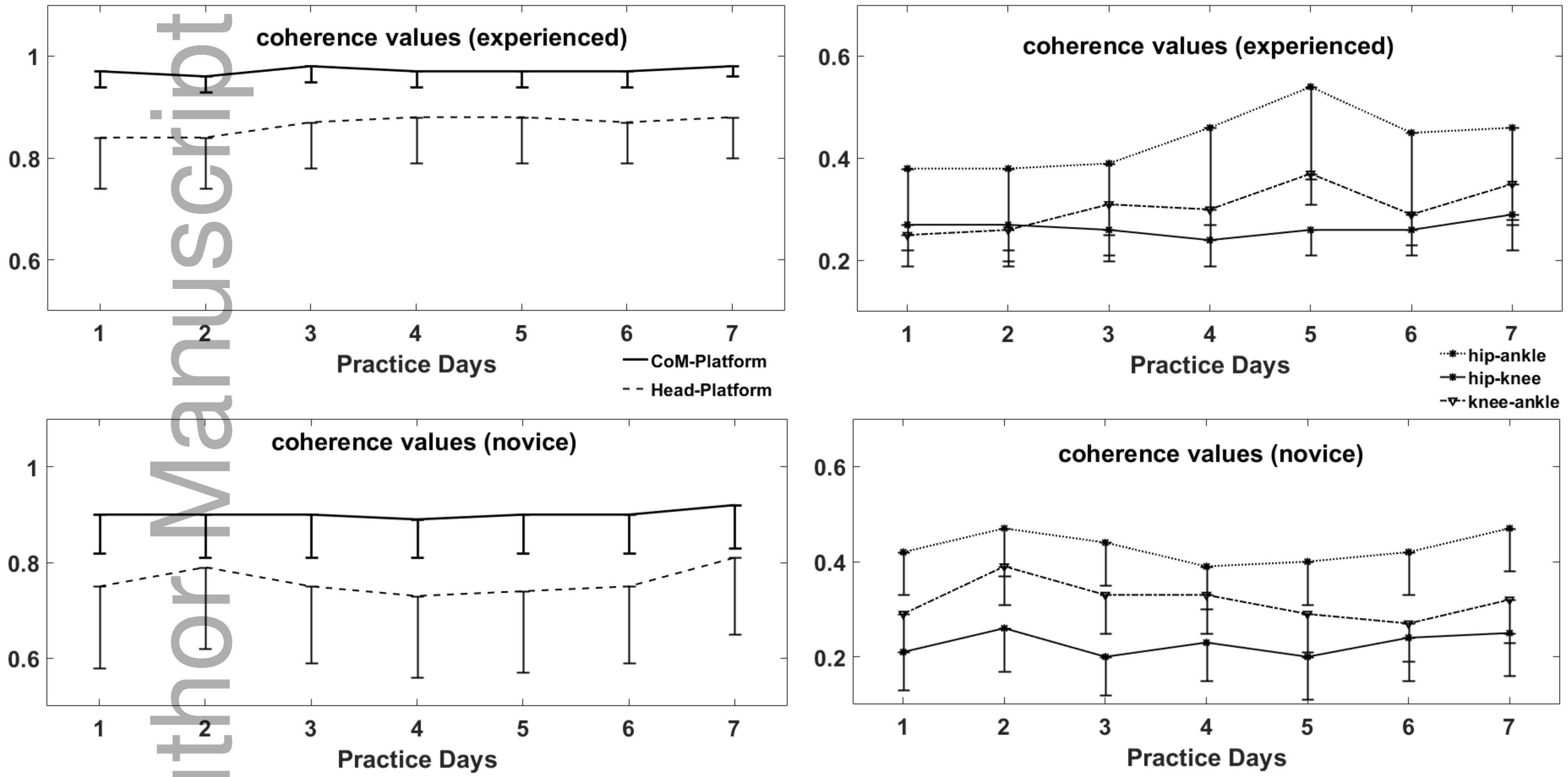

180
120
60
0
angle (deg)
cophase values (experienced)
1
2
3
4
5
6
7
Practice Days
180
120
60
0
angle (deg)
cophase values (novice)
CoM-plat
head-plat
hip-ankle
hip-knee
knee-ankle
1
2
3
4
5
6
7
Practice Days

Figure 5.


coherence values (experienced)
1
0.8
0.6
1 2 3 4 5 6 7
Practice Days
CoM-Platform
Head-Platform
coherence values (experienced)
0.6
0.4
0.2
1 2 3 4 5 6 7
Practice Days
hip-ankle
hip-knee
knee-ankle
coherence values (novice)
1
0.8
0.6
1 2 3 4 5 6 7
Practice Days
coherence values (novice)
0.6
0.4
0.2
1 2 3 4 5 6 7
Practice Days