# Effects of Cognitive- and Motor-Dual Tasks on Postural control Regularity following Anterior Cruciate Ligament Reconstruction

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## Abstract

**Background**: High injury rates following anterior cruciate ligament reconstruction (ACLR) motivate the need to better understand lingering movement deficiencies following return to sport. Athletic competition involves various types of sensory, motor, and cognitive challenges; however, postural control deficiencies during this spectrum of conditions are not well understood following ACLR.

**Research Question**: To what extent is postural control altered following ACLR in the presence of sensory, motor, and cognitive challenges, and does postural control correlate with patient-reported symptoms?

**Methods**: Fourteen individuals following ACLR (4m/10f, 21.2±2.4yr, 76.9±19.1kg, 1.70±0.14m) and fourteen matched healthy controls (4m/10f, 21.2±1.4yr, 75.4±15.3kg, 1.70±0.15m) participated in the study. Participants completed single-leg balance, ACLR limb or matched side for controls, under four conditions: 1) eyes open, 2) eyes closed, 3) visual-cognitive dual task (i.e., reverse digit span), and 4) motor dual task (i.e., catching a ball). Sample entropy (SEn) was calculated for each balance condition to characterize regularity of center of pressure control. Participants also completed patient-reported outcomes to characterize self-reported knee function, symptoms, and fear. A mixed effects model tested for differences in SEn between balance conditions, and Spearman correlations tested for relationships between SEn and patient-reported outcomes.

**Results**: A significant Group-by-Condition interaction was detected ($P = 0.043$). While the motor dual task and eyes closed balance conditions were associated with the lowest SEn for both groups, only the visual-cognitive dual task condition demonstrated a significant difference between groups, with the ACLR group having lower SEn [95% confidence interval for ΔSEn: (0.03, 0.35)]. Lower KOOS-Sport scores were associated with decreased SEn for the ACLR group ($\rho=0.81$, $P<0.001$).

**Significance**: These findings are consistent with ACLR individuals using a less automatic approach to postural control compared to controls, particularly when presented with a visual-cognitive challenge.

Altered neuromuscular control persists well after ACLR surgery and can be related to patient-reported outcomes.

## Introduction

Anterior cruciate ligament reconstructions (ACLR) are commonly performed to restore mechanical stability following ACL injury; however, neuroplastic changes [1-3], altered cognitive performance [4], and movement impairments [5] are still observed well after completing rehabilitation following ACLR. Up to 91% of young athletes return to strenuous sport following an ACLR [6], but approximately a third of these athletes will sustain a second ACL tear following ACLR surgery [7]. This persistent high risk of injury motivates the need to gain a more comprehensive understanding of neuromuscular alterations following ACLR.

There is growing evidence of neuroplastic changes in ACLR patients that are associated with altered sensory and cognitive processing for motor execution [2]. In particular, ACLR individuals demonstrate altered brain activation and connectivity patterns that are consistent with a potential sensory reweighting effect and increased cognitive and visual-spatial related activity for fundamental knee movement [8]. Supporting evidence for the biomechanical relevance of these changes include altered jump landing mechanics and postural control in ACLR patients during visual interference (i.e., stroboscopic glasses [9]) and a visual-cognitive task (i.e., reverse digit span [10]), respectively. Understanding specific scenarios that pose the greatest challenge following ACLR may reveal novel opportunities to advance rehabilitation efforts to ensure patients have do not demonstrate compensatory motor control strategies that would be maladaptive for sport environments.

ACLR individuals generally exhibit impaired balance during single-leg stance compared to healthy controls [11, 12], although recent findings suggest that single-leg balance under single-task conditions (i.e., without additional cognitive or motor tasks) may not be sensitive enough to detect impairments [13]. Our prior work using traditional center of pressure (CoP) measures (i.e., 95% confidence ellipse area) indicated that secondary motor and eyes closed conditions elicit the largest increases in postural sway compared to eyes open or a visual-cognitive dual task; however, the visual-cognitive dual task was the only condition where group differences between ACLR and matched healthy controls was discernable [10]. These findings provide further support for potential ACLR specific neural processing interference during visual-cognitive dual-task scenarios [14, 15].

The majority of prior studies regarding postural control impairments following ACLR have focused on gross balance control or traditional CoP measures [12, 16-18]. While these measures provide important information, they do not characterize the time-dependent nature of postural control (i.e., how the CoP is controlled throughout time). A number of nonlinear measures, such as sample entropy (SEn), have been used in postural control research to provide this complementary information. SEn characterizes the regularity of a time series and has been proposed as a marker of automaticity when applied to postural control (i.e., decreased SEn is associated with more regular CoP signals and interpreted as less automatic approach to postural control) [19, 20]. Determining scenarios (e.g., visual-cognitive challenges) that elicit less automatic postural control following ACLR is an underexplored opportunity to better understand altered motor control strategies that can guide future rehabilitation development.

The purpose of this study was to better understand altered postural control following ACLR in the presence of sensory, motor, and cognitive challenges. We hypothesized that ACLR individuals would exhibit greater increases in CoP regularity in response to removing vision or introducing cognitive challenge compared to healthy controls. Additionally, to evaluate the potential clinical relevance of CoP regularity in ACLR individuals, we hypothesized that worse self-reported knee function in the ACLR group would be associated with increased CoP regularity.

## Materials and Methods

### *Participants*

This manuscript represents a secondary analysis of data originally collected with the intent to investigate differences in traditional, linear measures of postural sway between ACLR and healthy control groups [10]. Methodological details related to the purpose and hypothesis of the current manuscript are discussed below, but additional details can be found elsewhere [10].

Individuals having returned to unrestricted activity following an ACLR surgery and healthy controls matched on an individual level based on age, sex, height, weight, and activity level were recruited for this study. Activity level was determined using the Tegner and Marx activity scales [21, 22]. ACLR individuals were excluded if they had pain or joint effusion at the time of testing. Healthy control participants were excluded if they had a previous musculoskeletal surgery or time-loss injury. Additional exclusion criteria for both groups included a history of vestibular or neurological disorders, uncorrected visual impairment, and history of learning disability, dyslexia, or ADD/ADHD.

### *Postural Control*

Single-leg stance was measured under four conditions: 1) eyes open (EO), 2) eyes closed (EC), 3) cognitive dual task (DC), and 4) motor dual task (DM) [10]. For each condition, three 20-second trials were collected where the CoP was measured at 1000 Hz using a balance plate (FP4060; Bertec Corp.; Columbus, OH). Participants were asked to stand as still as possible for each condition. The DC condition was a silent reverse digit span task [16, 23]. This task involved visually presenting a number every four seconds and then having the participant recite the list of numbers in reverse order at the conclusion of the balance trial. The DM condition consisted of participants catching a light plastic ball from a ball machine (Franklin Sports Inc., Stoughton, Massachusetts, USA) that was placed 4 meters away from the participant. Balls (2.75 inch diameter, ~ 30 grams) were tossed every 5 seconds in a parabolic trajectory to participants' chest at 6.71 m/sec. Participants kept their arms positioned so that their hands were able to catch the ball with minimal movement. They were required to catch the ball with both hands with minimal movement of their arms/body, which was facilitated by consistent ball trajectories from the ball machine. The order of the four balance conditions was randomized. Both limbs were assessed, but analysis focused on the reconstructed limb in the ACLR group and matched side for the control group.

Processing of CoP data was performed using custom MATLAB code (version R2017a; Mathworks, Natick, MA). Sample entropy (SEn) was calculated for increment resultant CoP [24]. The increment resultant is calculated by differencing the resultant CoP time series. Data were downsampled to

50 Hz without filtering, then demeaned and divided by standard deviation. We assumed m = 3 based on previous studies [19, 24], and identified r = 0.25*(standard deviation) through an optimization procedure on the ACLR data [25]. The directionality and statistical significance of differences and correlations reported in this study did not differ over a range of r = 0.2 to r = 0.3 (**Supplemental Material**), supporting the robustness of the results to modest changes in the tolerance value [26]. SEn characterizes the degree of regularity in the CoP dynamics. Increased SEn indicates less regularity in CoP control, which was interpreted as healthier, more automatic postural control [19, 24, 27], although we acknowledge there is likely an upper limit of the degree of irregularity that is deemed healthy.

### *Surrogate Analysis*

Surrogate datasets were used to distinguish whether the nonlinear dynamics of the CoP signals as measured by SEn were solely a product of a random process. Time-randomized CoP data for each trial were calculated by randomly reordering datapoints within a given trial. This transformation destroys temporal correlations [28]. Additionally, the original CoP data were phase-randomized, which retains linear correlations [28, 29]. For each surrogation method, a single surrogate trial was calculated from each of the original time series trials collected (n = 336), with the 3-trial average being used as the estimate for each participant-condition and surrogation method. Statistically significant increases (see end of Statistical Analysis section) in SEn for the surrogate datasets were interpreted as support for the original data and its associated findings being due to nonlinear structure of the CoP data.

### *Patient-Reported Outcomes*

Several patient-reported outcomes (PROs) were administered to characterize participants' physical activity, activity level, knee function and symptoms, and psychological outlook on knee function. The Knee Injury and Osteoarthritis Outcome Score (KOOS) assessed subscales of Pain, Symptoms, Activities of Daily Living (ADL), Sports and Recreation Function (Sport), and Knee-related Quality of Life (QOL) [30]. The ACL-Return to Sport Index (ACL-RSI) was used to assess psychological perspective on knee function [31]. Additionally, the shortened Tampa Scale for Kinesiophobia (TSK-11) was administered to characterize participants' pain-related fear of movement and/or reinjury [32]. The International Knee Documentation Committee Subjective Knee Form (IKDC-SKF) was also administered as a measure of symptoms, function, and sport activities [33]. Higher scores on the KOOS, ACL-RSI, and IKDC-SKF are representative of better outcomes, while higher scores on the TSK-11 is associated with worse fear.

### *Power Analysis*

An *a priori* power analysis was not possible as no previous studies have reported the same dependent variable across the visual-motor and visual-cognitive tasks used in this current study. Therefore, we conducted a post-hoc estimation of statistical power using the dependent variable for this study (SEn). Power was calculated for a group-by-condition interaction using the Hotelling-Lawley trace test and null hypothesis that all mean differences were zero. Correlations were 0.006-0.665 between conditions and 0.567 between groups. For a Type 1 error rate of 0.05, the study had 86% power for detecting a group-by-condition interaction for a sample size of 14 matched pairs. Power calculations were conducted using General Linear Mixed Model Power and Sample Size (GLIMMPSE) 3.0 (see **Table 2** for means and standard deviations used in the power analysis) [34].

### *Statistical Analysis*

All statistical analyses were performed in Minitab (version 18.1; Minitab, Inc., State College, PA). Paired t-tests were used to test for differences between groups for demographic variables and PROs [10]. To identify group differences, mixed effects models were used that included subject pair as a random factor, and group (CON, ACLR), balance condition (EO, EC, DC, DM), and group-by-condition as fixed effects. Tukey post-hoc pairwise comparisons were performed for significant interaction and main effects with a significance level of $\alpha = 0.05$, with *P*-values presented being adjusted for multiple comparisons. Effect sizes for pairwise differences were estimated using pairwise differences, standard error of differences, and degrees of freedom values provided by the simultaneous Tukey post-hoc comparisons for the mixed effects model (i.e., ES = difference of means/((SE of differences)*√(DF))). Note, this ES differs from a traditional Cohen's d effect size that is based on the unpaired group means and standard deviations, although this can be calculated from the data presented in Table 2.

Additionally, Spearman correlations were used to identify relationships between balance outcomes and eight PRO scales (ACL-RSI, TSK-11, IKDC-SKF, KOOS-Pain, KOOS-Symptoms, KOOS-ADL, KOOS-Sport, KOOS-QOL). Significance level for the correlations was corrected for the eight PRO scales ($\alpha = 0.05/8 = 0.006$) in an attempt to mitigate the effect of the multiple comparisons due to the numerous PRO measures. A bootstrapping process (1000 iterations of sampling with replacement) was performed for significant associations to identify the sensitivity of the correlation point estimate to individual participants (MATLAB). Because the healthy control group was largely clustered at the ceiling of the PRO scales, the correlation analysis was only done for the ACLR group and was considered separately for each balance condition.

Finally, the mixed effects model was rerun with 'data type' (original, time-, or phase-randomized) as an added fixed effect to test for differences between original and surrogate data.

## Results

Fifteen individuals following ACLR and 15 age-, sex-, height-, and weight-matched controls participated in the study. One matched pair was excluded due to data collection issues with one participant, leaving 14 matched pairs for analysis (**Table 1**). There were no significant differences between groups for age, mass, or height (**Table 1**). Groups did not differ on Tegner activity level at the time of testing or during participants highest level, but the ACLR group did report significantly worse symptoms (descriptive statistics for PROs are reported in [10]).

[INSERT TABLE 1]

A significant group-by-condition interaction was observed ($F_{3,91}$=2.83; *P* = 0.043; **Table 2**). Post-hoc analysis revealed that the interaction effect was driven by the DC condition, which was the only condition to demonstrate significant differences between the groups. Specifically, the ACLR group had lower SEn (ES = 0.38; *P* = 0.01) during DC. Notably, the CON group did not demonstrate a significant change in SEn during DC compared to baseline (*P* = 1.0). There was a significant main effect of group for SEn ($F_{1,91}$=10.83; *P* = 0.001), with post-hoc analysis revealing that the ACLR group demonstrated decreased SEn compared to matched controls (ES = 0.34; *P* = 0.001). There was also a significant main effect of balance condition ($F_{3,91}$=45.81; *P* < 0.001) that revealed that the DM and EC conditions were generally associated with decreased SEn compared to the baseline and DC conditions.

[INSERT TABLE 2]

A significant association was observed between SEn and the KOOS-Sport (**Figure 1**). Lower KOOS-Sport scores were associated with increased CoP regularity during the DC condition for the ACLR group (ρ = 0.81 (95% CI: 0.71, 0.84), *P* < 0.001). No other associations reached statistical significance (all *P* > 0.01, see **Supplemental Material**).

[INSERT FIGURE 1]

The analysis of surrogate data found that SEn estimates obtained from the original data were significantly different from those of the phase- and time-shuffled data (**Figure 2**).

[INSERT FIGURE 2]

## Discussion

This study aimed to understand altered postural control following ACLR in the presence of sensory, cognitive, and motor challenges. Our hypotheses were partially supported. A visual-cognitive distraction resulted in significantly increased CoP regularity in the ACLR group compared to the healthy control group. Additionally, worse self-reported function during higher-level activities (i.e., KOOS-Sport) was associated with increased CoP regularity during the visual-cognitive dual task condition. Our findings highlight the utility of visual-cognitive dual-task conditions for assessing postural control following ACLR.

A visual-cognitive challenge elicited the greatest ACLR-specific effects on CoP regularity. The ACLR group showed increased CoP regularity in the presence of a cognitive secondary task while the CON group showed no change, and self-reported knee dysfunction was associated with increased CoP regularity when a visual-cognitive secondary task was present for the ACLR group. These findings are consistent with ACLR individuals increasing cognitive attention devoted toward balance and/or adopting a ‘posture first’ strategy in the presence of cognitive distractions [19, 24, 35]. Similar findings (i.e., decreased CoP regularity with the addition of a cognitive task) were previously observed for ACL-deficient participants; however, this increase in regularity was similar between ACL-deficient and healthy controls when using other analytical techniques (i.e.. Shannon entropy) and CoP time series (i.e., medial-lateral and anterior-posterior CoP time series) [36]. Additionally, the increased regularity in the presence of a cognitive task observed in our study contradicts other reports in healthy individuals where CoP regularity decreases with increasing cognitive challenge during bipedal standing balance [37, 38]. Greater attention devoted to balance is thought to hinder the typically efficacious ‘automatic’ postural control in healthy adults. ACLR individuals’ impaired sensory information and/or conscious awareness of knee dysfunction may contribute to the increased CoP regularity in the ACLR group compared to healthy controls. Our findings provide new insight into the time-ordered CoP control and suggest that ACLR individuals demonstrate altered control during single-leg stance when also challenged by a cognitive task. Under the relationship observed in our study, adopting a compensatory strategy of increasing attention for motor tasks could potentially exacerbate neuromuscular deficiencies when attention is required to be placed elsewhere (e.g., visual-cognitive dual task in our study or reacting to an opponent during competition). Future research is warranted to elucidate whether altered attentional investment in these dual-task scenarios is a clinically-relevant target for mitigating ACL re-injury risk.

In the current study, the tasks with the greatest increases in CoP regularity (i.e., EC and DM conditions) did not demonstrate differences between ACLR individuals and healthy controls, which is consistent with previous findings [10, 11, 39]. In contrast, the group differences were specific to the visual-cognitive dual-task condition for the current study. It is also noteworthy that the DC condition had higher SEn values than the EC and DM conditions, which suggests participants may have used a more automatic postural control strategy when attention was drawn to the visual-cognitive task compared to when the task goal required participants to be particularly still in order to be in position to catch the ball (i.e., DM). The relative increase in SEn from EC to DC corroborates previous findings that have interpreted this as a change in the focus of attention from internal during EC to the cognitive task during DC [19]. These findings motivate the need for more detailed investigations into cognitive stimuli that present ACLR individuals with the greatest challenge and may pose the highest risk for deleterious neuromuscular control.

The lack of group differences during the EC condition did not support our hypothesis. This hypothesis was based on the increased reliance on visual information for motor control following ACLR [9]. However, our current findings are consistent with previous analyses [12, 18]. It is possible that this lack of significant findings is due to the increased difficulty of the task regardless of group. This concept is supported by EC having the largest postural sway of the conditions we tested for both groups [10]. Although the lack of EC effects may be simply driven by the condition being very unstable and eliciting similar adaptations (e.g., increasing joint stiffness) between groups [40], it is plausible that a combined visual-cognitive challenge (and not simply a visual knockout) is better suited to detect the ACLR specific differences.

This study presents novel findings regarding altered CoP regularity in ACLR individuals during cognitively-challenging quiet stance; however, there are several limitations that should be considered in interpreting the findings. First, interpretating increases in SEn as being more automatic, healthier postural control has limitations. This interpretation is likely overly simplistic in that it does not account for the probable existence of an upper bound of 'healthy' irregularity, above which may be suboptimal. Additionally, our experimental protocol included instructions for participants to be as still as possible may have artificially decreased the automaticity of postural control when participating in the study. However, we believe the impact of this on the relative differences between groups and conditions for this study is mitigated because the instructions remained consistent. The chosen template length for the SEn calculation (i.e., $m = 3$) results in ~60 msec, which may limit the ability to capture contributions to postural control that occur on longer time scales (e.g., supraspinal contributions). Although limitations and open questions remain regarding physiological interpretations of SEn and its calculation, the methods used in the current study have previously shown support for increases in SEn being associated with increased automaticity of postural control [24], which was the motivation for using this interpretation in this study.

Additional limitations include that the ACLR cohort was recruited from a convenience sample in a university setting, which is susceptible to self-selection bias and therefore, the sample may not fully represent a completely random sample of ACLR individuals with similar demographics. Furthermore, the cognitive stimulus was presented visually and may have facilitated a visual anchor effect where postural control is altered to improve the ability to identify the stimulus. The performance on the cognitive task was not recorded, so it is unknown if cognitive performance was sacrificed during DC balance, which has previously been reported [17]. Additionally, including validated measures of cognitive ability may improve identification of potential mediating relationships for cognitive-motor dual task performance [41]. Despite these limitations, the findings build on previous research to better identify altered CoP regularity in ACLR individuals and highlight altered cognitive-motor performance following ACLR.

## Conclusion

Individuals following ACLR demonstrated altered postural control at least one year following surgery compared to uninjured controls. Differences in single-leg balance between groups were most pronounced under concurrent visual-cognitive challenge, which elicited increased CoP regularity in a group following ACLR relative to controls. CoP regularity during cognitive dual task was also associated with self-reported function during high-level activities. These results further support altered neuromuscular control that persists well after ACLR surgery, even in individuals who return to at least a recreational activity level.

**Conflicts of Interest:** None

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## References

[1] A.S. Lepley, D.R. Grooms, J.P. Burland, S.M. Davi, J.M. Kinsella-Shaw, L.K. Lepley, Quadriceps muscle function following anterior cruciate ligament reconstruction: systemic differences in neural and morphological characteristics, Exp Brain Res 237(5) (2019) 1267-1278. https://www.ncbi.nlm.nih.gov/pubmed/30852644.
[2] D.R. Grooms, S.J. Page, D.S. Nichols-Larsen, A.M. Chaudhari, S.E. White, J.A. Onate, Neuroplasticity Associated With Anterior Cruciate Ligament Reconstruction, J Orthop Sports Phys Ther 47(3) (2017) 180-189. https://www.ncbi.nlm.nih.gov/pubmed/27817301.
[3] E. Kapreli, S. Athanasopoulos, J. Gliatis, M. Papathanasiou, R. Peeters, N. Strimpakos, et al., Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study, Am J Sports Med 37(12) (2009) 2419-26. https://www.ncbi.nlm.nih.gov/pubmed/19940314.
[4] A.E. Stone, J.A. Roper, D.C. Herman, C.J. Hass, Cognitive Performance and Locomotor Adaptation in Persons With Anterior Cruciate Ligament Reconstruction, Neurorehabil Neural Repair 32(6-7) (2018) 568-577. https://www.ncbi.nlm.nih.gov/pubmed/29779423.
[5] M.V. Paterno, K.R. Ford, G.D. Myer, R. Heyl, T.E. Hewett, Limb Asymmetries in Landing and Jumping 2 Years Following Anterior Cruciate Ligament Reconstruction, Clinical Journal of Sport Medicine 17 (2007).
[6] J. Kay, M. Memon, R.G. Marx, D. Peterson, N. Simunovic, O.R. Ayeni, Over 90 % of children and adolescents return to sport after anterior cruciate ligament reconstruction: a systematic review and meta-analysis, Knee Surg Sports Traumatol Arthrosc 26(4) (2018) 1019-1036. https://www.ncbi.nlm.nih.gov/pubmed/29332225.
[7] T.J. Dekker, J.A. Godin, K.M. Dale, W.E. Garrett, D.C. Taylor, J.C. Riboh, Return to sport after pediatric anterior cruciate ligament reconstruction and its effect on subsequent anterior cruciate ligament injury, Journal of Bone and Joint Surgery - American Volume 99 (2017) 897-904.
[8] C.R. Criss, J.A. Onate, D.R. Grooms, Neural activity for hip-knee control in those with anterior cruciate ligament reconstruction: A task-based functional connectivity analysis, Neuroscience Letters 730 (2020) 134985. https://dx.doi.org/10.1016/j.neulet.2020.134985.
[9] D.R. Grooms, A. Chaudhari, S.J. Page, D.S. Nichols-Larsen, J.A. Onate, Visual-Motor Control of Drop Landing After Anterior Cruciate Ligament Reconstruction, J Athl Train 53(5) (2018) 486-496. https://www.ncbi.nlm.nih.gov/pubmed/29749751.
[10] S.C. Miko, J.E. Simon, S.M. Monfort, J.P. Yom, S. Ulloa, D.R. Grooms, Postural stability during visual-based cognitive and motor dual-tasks after ACLR, Journal of Science and Medicine in Sport (2020). https://dx.doi.org/10.1016/j.jsams.2020.07.008.
[11] R.A. Clark, B. Howells, Y.H. Pua, J. Feller, T. Whitehead, K.E. Webster, Assessment of standing balance deficits in people who have undergone anterior cruciate ligament reconstruction using traditional and modern analysis methods, J Biomech 47(5) (2014) 1134-7. https://www.ncbi.nlm.nih.gov/pubmed/24433669.
[12] B.E. Howells, C.L. Ardern, K.E. Webster, Is postural control restored following anterior cruciate ligament reconstruction? A systematic review, Knee Surgery, Sports Traumatology, Arthroscopy 19 (2011) 1168-1177.
[13] S.G. Bodkin, L.V. Slater, G.E. Norte, J. Goetschius, J.M. Hart, ACL reconstructed individuals do not demonstrate deficits in postural control as measured by single-leg balance, Gait & Posture 66 (2018) 296-299. https://dx.doi.org/10.1016/j.gaitpost.2018.06.120.
[14] M. Chaput, J.A. Onate, J.E. Simon, C.R. Criss, S. Jamison, M. McNally, et al., Visual cognition associated with knee proprioception, time to stability, and sensory integration neural activity after ACL reconstruction, J Orthop Res (2021). https://www.ncbi.nlm.nih.gov/pubmed/33620108.

[15] S.G. Bodkin, J. Hertel, J.M. Hart, Gaze Accuracy Differences During Single-Leg Balance Following Anterior Cruciate Ligament Reconstruction, J Sport Rehabil (2021) 1-7. https://www.ncbi.nlm.nih.gov/pubmed/33503587.

[16] H. Negahban, P. Ahmadi, R. Salehi, M. Mehravar, S. Goharpey, Attentional demands of postural control during single leg stance in patients with anterior cruciate ligament reconstruction, Neurosci Lett 556 (2013) 118-23. https://www.ncbi.nlm.nih.gov/pubmed/24157849.

[17] S. Mohammadi-Rad, M. Salavati, I. Ebrahimi-Takamjani, B. Akhbari, S. Sherafat, H. Negahban, et al., Dual-Tasking Effects on Dynamic Postural Stability in Athletes With and Without Anterior Cruciate Ligament Reconstruction, J Sport Rehabil 25(4) (2016) 324-329. https://www.ncbi.nlm.nih.gov/pubmed/27632858.

[18] M. Dauty, S. Collon, C. Dubois, Change in posture control after recent knee anterior cruciate ligament reconstruction?, Clinical physiology and functional imaging 30 (2010) 187-191.

[19] S.F. Donker, M. Roerdink, A.J. Greven, P.J. Beek, Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control, Experimental Brain Research 181 (2007) 1-11.

[20] J.S. Richman, D.E. Lake, J. Moorman, Sample Entropy, Methods in Enzymology 384 (2004) 172-184.

[21] Y. Tegner, J. Lysholm, Rating systems in the evaluation of knee ligament injuries., Clin Orthop Relat Res. (1985) 43-49.

[22] R.G. Marx, T.J. Stump, E.C. Jones, T.L. Wickiewicz, R.F. Warren, Development and evaluation of an activity rating scale for disorders of the knee, Am J Sports Med 29(2) (2001) 213-8. https://www.ncbi.nlm.nih.gov/pubmed/11292048.

[23] H. Negahban, M.R. Hadian, M. Salavati, M. Mazaheri, S. Talebian, A.H. Jafari, et al., The effects of dual-tasking on postural control in people with unilateral anterior cruciate ligament injury, Gait Posture 30(4) (2009) 477-81. https://www.ncbi.nlm.nih.gov/pubmed/19709885.

[24] M. Roerdink, P. Hlavackova, N. Vuillerme, Center-of-pressure regularity as a marker for attentional investment in postural control: A comparison between sitting and standing postures, Human Movement Science 30 (2011) 203-212.

[25] D.E. Lake, J.S. Richman, M.P. Griffin, J. Moorman, Sample entropy analysis of neonatal heart rate variability., Am J Physiol Regul Integr Comp Physiol 283 (2002) R789--R797.

[26] J.M. Yentes, P.C. Raffalt, Entropy Analysis in Gait Research: Methodological Considerations and Recommendations, Annals of Biomedical Engineering (2021). https://dx.doi.org/10.1007/s10439-020-02616-8.

[27] J.F. Stins, M.E. Michielsen, M. Roerdink, P.J. Beek, Sway regularity reflects attentional involvement in postural control: Effects of expertise, vision and cognition, Gait and Posture 30 (2009) 106-109.

[28] S.A. Myers, Surrogation, in: N. Stergiou (Ed.) Nonlinear Analysis for Human Movement Variability, CRC Press, 2016, pp. 111-171.

[29] Temu, 2017. Surrogate Data. MATLAB Central File Exchange. https://www.mathworks.com/matlabcentral/fileexchange/4612-surrogate-data.

[30] E.M. Roos, H.P. Roos, L.S. Lohmander, C. Ekdahl, B.D. Beynnon, Knee Injury and Osteoarthritis Outcome Score (KOOS)--development of a self-administered outcome measure, J Orthop Sports Phys Ther 28(2) (1998) 88-96. https://www.ncbi.nlm.nih.gov/pubmed/9699158.

[31] K.E. Webster, J.A. Feller, C. Lambros, Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery, Physical Therapy in Sport 9(1) (2008) 9-15. https://dx.doi.org/10.1016/j.ptsp.2007.09.003.

[32] S.Z. George, T.A. Lentz, G. Zeppieri, D. Lee, T.L. Chmielewski, Analysis of shortened versions of the tampa scale for kinesiophobia and pain catastrophizing scale for patients after anterior cruciate ligament reconstruction, The Clinical journal of pain 28 (2012) 73-80.

[33] J.J. Irrgang, A.F. Anderson, A.L. Boland, C.D. Harner, M. Kurosaka, P. Neyret, et al., Development and validation of the International Knee Documentation Committee Subjective Knee Form., The American journal of sports medicine 29 (2001) 600-613.

[34] S. Kreidler, K. Muller, G. Grunwald, B. Ringham, Z. Coker-Dukowitz, U. Sakhadeo, et al., GLIMMPSE: Online Power Computation for Linear Models with and without a Baseline Covariate, Journal of Statistical Software 54(10) (2013).

[35] M. Roerdink, M. De Haart, A. Daffertshofer, S.F. Donker, A.C.H.H. Geurts, P.J. Beek, Dynamical structure of center-of-pressure trajectories in patients recovering from stroke, Experimental Brain Research 174 (2006) 256-269.

[36] H. Negahban, M. Salavati, M. Mazaheri, M.A. Sanjari, M.R. Hadian, M. Parnianpour, Non-linear dynamical features of center of pressure extracted by recurrence quantification analysis in people with unilateral anterior cruciate ligament injury, Gait and Posture 31 (2010) 450-455.

[37] N. Polskaia, Y. Lajoie, Reducing postural sway by concurrently performing challenging cognitive tasks, Human Movement Science 46 (2016) 177-183.

[38] G. St-Amant, T. Rahman, N. Polskaia, S. Fraser, Y. Lajoie, Unveilling the cerebral and sensory contributions to automatic postural control during dual-task standing, Human Movement Science 70 (2020) 102587. https://dx.doi.org/10.1016/j.humov.2020.102587.

[39] B.E. Howells, R.A. Clark, C.L. Ardern, A.L. Bryant, J.A. Feller, T.S. Whitehead, et al., The assessment of postural control and the influence of a secondary task in people with anterior cruciate ligament reconstructed knees using a Nintendo Wii Balance Board, Br J Sports Med 47(14) (2013) 914-9. https://www.ncbi.nlm.nih.gov/pubmed/23268373.

[40] I.C. Lee, M.M. Pacheco, K.M. Newell, Constraints specific influences of vision, touch and surface compliance in postural dynamics, Gait Posture 59 (2018) 117-121. https://www.ncbi.nlm.nih.gov/pubmed/29028623.

[41] S.M. Monfort, J.J. Pradarelli, D.R. Grooms, K.A. Hutchison, J.A. Onate, A.M.W. Chaudhari, Visual-Spatial Memory Deficits Are Related to Increased Knee Valgus Angle During a Sport-Specific Sidestep Cut, Am J Sports Med 47(6) (2019) 1488-1495. https://www.ncbi.nlm.nih.gov/pubmed/30986095.

**Figure Captions**

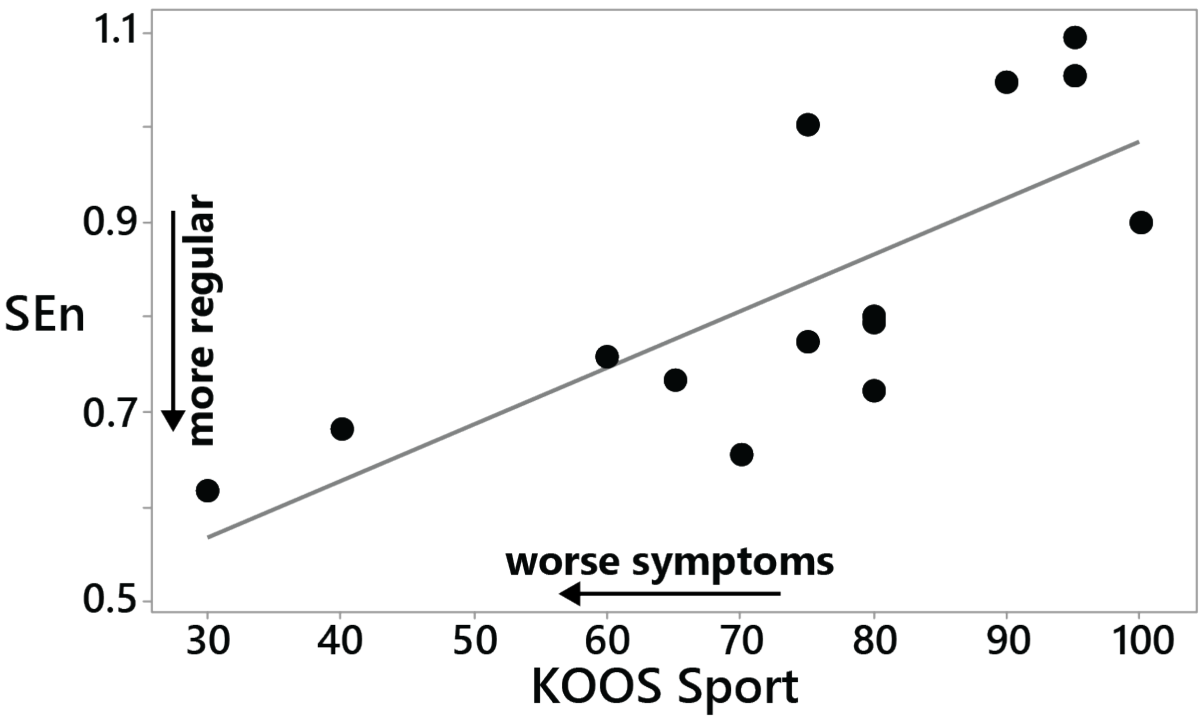

**Figure 1.** Correlation between the KOOS-Sport patient-reported outcome and sample entropy (SEn) for the ACLR group during the visual-cognitive dual task condition. Worse knee function on the KOOS-Sport was associated with increased center of pressure regularity (ρ = 0.81 (95% CI: 0.71, 0.84), *P* < 0.001).

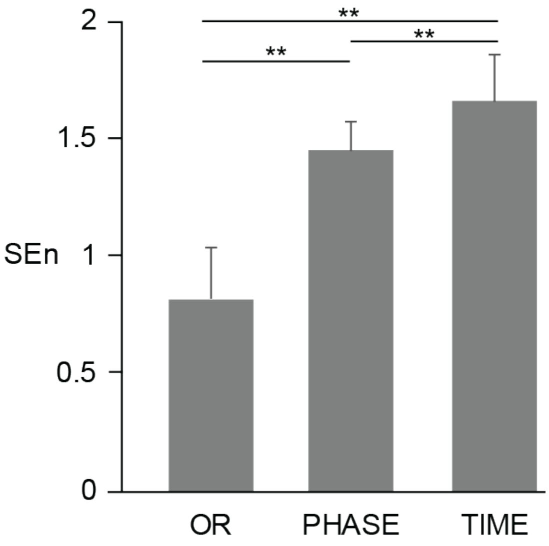

**Figure 2.** Comparisons of the original, time-randomized, and phase-randomized datasets for SEn. Data shown are collapsed across both groups and all testing conditions. SEn was significantly lower for the original dataset than both of the surrogate datasets. ** indicates $P < 0.001$.

## Tables

**Table 1.** Demographics and surgical information**.** Data presented as mean ± SD unless otherwise noted.

| **Variable** | **CON** | **ACLR** | ***P*-value** |
|---|---|---|---|
| **Age (years)** | 21.2 ± 1.4 | 21.2 ± 2.4 | 1 |
| **Mass (kg)** | 75.4 ± 15.3 | 76.9 ± 19.1 | 0.66 |
| **Height (m)** | 1.7 ± 0.15 | 1.7 ± 0.14 | 0.99 |
| **Sex (m/f)** | 4/10 | 4/10 | 1 |
| | | | |
| **ACLR Graft Type** | | | |
| **Hamstring, n (%)** | - | 9 (64%) | |
| **Patellar Tendon, n (%)** | - | 4 (29%) | |
| **Allograft, n (%)** | - | 1 (7%) | |
| **Injured Leg (R/L)** | - | 6/8 | |
| **Weeks Since Surgery** | - | 202.1 ± 122.1<br>(range: 56 - 469) | |

**Table 2.** Sample entropy values across the four balance conditions and results of the mixed effect model for group, condition, and group-by-condition effects.

| | | **Condition (mean ± SD)** | | | | **Mixed Effects Model Factors (*P*-values)** | | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **Group** | **EO** | **EC** | **DC** | **DM** | **Group** | **Condition** | **Group*Condition** |
| **SEn** | **CON** | 1.03 ± 0.11 | 0.80 ± 0.18 | 1.02 ± 0.09 | 0.59 ± 0.17 | **0.001*** | **<0.001*** | **0.043*** |
| | **ACLR** | 0.95 ± 0.17 | 0.71 ± 0.15 | 0.83 ± 0.16 | 0.61 ± 0.17 | CON > ACLR | EO, DC > EC > DM | $CON_{DC} > ACLR_{DC}$ |

* indicates statistical significance ($p<0.05$)

SEn [arbitrary units]