

Potential Mediators of Load-Related Changes in Movement Complexity in Young, Healthy Adults

Stephen M. Glass, PhD*; Christopher K. Rhea, PhD†; Randy J. Schmitz, PhD, LAT, ATC†; Scott E. Ross, PhD, LAT, ATC, FNATA†

*Department of Otolaryngology, The Ohio State University, Columbus; †Department of Kinesiology, The University of North Carolina at Greensboro

Context: Movement screening has become increasingly popular among tactical professionals. This popularity has motivated the design of interventions that cater to improving outcomes on the screens themselves, which are often scored in reference to an objective norm. In contrast to the assumptions underlying this approach, dynamical systems theory suggests that movements arise as a function of continuously evolving constraints and that optimal movement strategies may not exist. To date, few data address behavioral complexity in the fundamental movement tasks commonly used in clinical screenings.

Objective: To provide evidence of complex variability during movement screens and test the role of modifiable—that is, trainable—constraints in mediating loss of complexity during experimental-task manipulations.

Design: Crossover study.

Setting: Research laboratory.

Patients or Other Participants: Twenty-five male (age = 23.96 ± 3.74 years, height = 178.82 ± 7.51 cm, mass = 79.66 ± 12.66 kg) and 25 female (age = 22.00 ± 2.02 years, height = 165.40 ± 10.24 cm, mass = 63.98 ± 11.07 kg) recreationally active adults.

Intervention(s): Participants performed tests of balance, range of motion, and strength. Additionally, they performed cyclical movement tasks under a control (C) condition and while wearing an 18.10-kg weight vest (W).

Main Outcome Measure(s): Ground reaction forces were sampled at 1000 Hz and used to calculate center of pressure during cyclical movement tests. Multivariate multiscale entropy (MMSE) for the center-of-pressure signal was then calculated. Condition effects (C versus W) were analyzed using paired *t* tests, and penalized varying-coefficients regression was used to identify models predicting entropy outcomes from balance, range of motion, and strength.

Results: The MMSE decreased during the W condition ($MMSE_C > MMSE_W$; t_{49} range = 3.17–5.21; all *P* values < .01).

Conclusions: Moderate evidence supported an association between modifiable constraints and behavioral complexity, but a role in mediating load-related loss of complexity was not demonstrated.

Key Words: weight bearing, postural balance, muscle strength

Key Points

- Standardized external loading is associated with decreased multiscale complexity during commonly used clinical assessments of functional movement.
- Modifiable constraints on movement behavior, namely balance and range of motion, may contribute to movement complexity.
- Except for dorsiflexion range of motion, modifiable constraints did not mediate load-related decreases in movement complexity.

This article is the second installment of a 2-part work on movement-quality screens. Our purpose was to present original research that expands the context in which these clinical findings are interpreted, with particular emphasis on their use among tactical professional communities. Additionally, we attempted to integrate solutions to methodologic challenges that have thus far limited which theories concerning movement screens can be tested scientifically. The central theme in this research was that movement-quality outcomes can provide useful clinical information for a given client or athlete but that promoting invariant patterns of movement behavior should not be the default approach. We take no position regarding the author-intended use of any particular screen; rather, we focus on the prevailing clinical practices in which such screens are

used. In part 1, we discussed the relationship between clinically derived movement-screen outcomes (ie, observer ratings of movement quality) and modifiable intrinsic factors when the movement screen was administered with or without an external load. In this installment, we consider the influence of these same constraints on the dynamical behavior of the movement system when similar movement patterns are performed repetitively.

In the last decade, the development and adoption of clinical movement-quality screens has increased dramatically.^{1–4} Although their uses are generally quite broad, a common area of application is among the community of tactical professionals.^{5,6} These professionals must strike a delicate balance between performance optimization and preventing musculoskeletal injuries⁷ and, therefore, stand to

benefit from expanding the focus of training beyond volume and intensity to incorporate concepts such as movement quality. Thus, movement screens hold considerable appeal for this population.

When movement-quality assessments are used as a predictive or screening tool, their popularity has merit. However, as is often the case with tests of any kind, intervention programs have been designed to improve performance on the test itself.^{8,9} The distinction between a screen and an indication for intervention is subtle but very important. When used for the latter purpose—particularly in the context of group studies—movement-quality assessments carry the potentially problematic assumption that generic, optimal patterns of movement behavior should be the criterion of interest.^{10,11} An alternative perspective would suggest that physiological systems are constantly attempting to adjust to a set of constraints that evolve continuously over time.^{12,13} It is possible, therefore, that invariant patterns of movement should not be encouraged without considering these constraints.

Whereas the clinical literature may refer to movement as *functional* or *dysfunctional*,^{14,15} the variability of the movement (rather than the movement itself) may be more telling in this regard. Specifically, the structure of the variability is most relevant. Those individuals who are relatively unencumbered by intrinsic constraints on movement are able to adapt more seamlessly to changing demands related to the task or environment.¹² In these cases, movement behaviors exhibit a complex variability structure,¹⁶ which may be seen as reflecting effective adaptation to a changing profile of constraints. This can be true even in tasks with very small margins for error, such as during skilled sport performance or shooting,¹⁷ during which compensatory variability in movement can be used to maintain consistency with respect to the outcome. To define a benchmark movement strategy as optimal risks discounting the relevance of ever-changing constraints, along with the functional variability that follows in a healthy, adaptable system. Rather than training solely to achieve such a benchmark in the movement itself, it may be equally important to focus on identifying and modifying intrinsic constraints that limit the adaptability of the movement system.

Balance, range of motion, and strength have been suggested to be important determinants of clinically rated movement quality^{1,2,18,19} and may provide insight into such constraining influences on adaptability in common movement patterns. The motivation for our study was to show evidence of constrained optimization—as opposed to absolute optimization—in discrete, fundamental movement tasks. In applied terms, this distinction can be extended to address the question, “To what extent should interventions be directed toward the movement pattern versus potential underlying factors such as strength or flexibility?” Our specific purpose for this work was to quantify the roles of balance, range of motion, and strength in promoting dynamical complexity during tasks commonly used as clinical assessments of movement quality. Data of this kind are very limited, as most of the available analytical techniques are better suited to the study of continuous movements, such as gait or quiet standing, than movements that occur over relatively few cycles.

Experimental manipulation of task constraints adds an important within-subjects dimension when studying the dynamical of human behavior, where outcomes may be sensitive to particular data-processing techniques.²⁰ As such, we also sought to determine the extent to which balance, range of motion, and strength mitigate the loss of complexity related to external load carriage—an ecologically valid treatment for the tactical professional—during the same tasks. We hypothesized that (1) higher levels of balance, range of motion, and strength would predict greater complexity and (2) these same attributes would prevent the loss of complexity associated with external loading.

METHODS

This investigation was approved by the institutional review board of the University of North Carolina at Greensboro. All participants provided written informed consent before data collection began. Fifty recreationally active adults (25 men: age = 23.96 ± 3.74 years, height = 178.82 ± 7.51 cm, mass = 79.66 ± 12.66 kg; 25 women: age = 22.00 ± 2.02 years, height = 165.40 ± 10.24 cm, mass = 63.98 ± 11.07 kg) were recruited to participate in this investigation. This population was chosen to reflect the candidate demographic for tactical professions.

Participants with clinical conditions that might affect the outcome measurements were excluded: eg, chronic instability of a lower extremity joint, any recent history of injury (<6 months before data collection), Ehlers-Danlos or joint hypermobility syndrome, uncorrected visual impairment not including astigmatism, vestibular disorder, peripheral sensory disorder, or any musculoskeletal condition requiring ongoing care from a licensed health care provider.

Procedures

Participants first completed a physical activity readiness questionnaire and demographic information survey and had their height and mass measured. They then completed all clinical and laboratory assessments during a single data-collection session. These measures are presented in the order in which they were administered.

Balance

Balance was assessed in quiet, single-legged stance for a period of 10 seconds in accordance with previous research on tactical athleticism.²¹ Single-legged stance was chosen as previous investigators²² concluded that double-legged standing may not be sensitive enough to detect meaningful differences in young, healthy populations. All testing was conducted using the nondominant limb, with the *dominant limb* defined as the leg the participant would use to kick a ball for maximum distance. Participants completed all tests barefoot with eyes closed, hands on hips, and a slight bend of the hip and knee in the nonstance leg. After a preliminary practice trial, each participant continued balance testing until he or she completed a successful trial (no loss of the testing position).

Ground reaction force data during quiet-stance balance testing were sampled at 100 Hz using an Accusway force plate (Advanced Mechanical Technology, Inc, Watertown, MA). Center-of-pressure (COP) coordinates were then

calculated in the anteroposterior and mediolateral directions using the Balance Clinic software package (Advanced Mechanical Technology, Inc). Anteroposterior and mediolateral COP data were combined to form a resultant time series using LabVIEW 2012 (National Instruments, Austin, TX). Mean velocity of the resultant time series (CP_V) was entered as a predictor in our models. Because CP_V may be more susceptible to filtering effects than other COP outcomes,²⁰ no filter was applied to the raw time series.

Range of Motion

Range of motion was quantified using 3 validated clinical measures. The Apley scratch test quantifies range of motion in the shoulders and thoracic spine, the sit-and-reach test measures hip and trunk flexibility, and the weight-bearing-lunge test measures dorsiflexion range of motion.

The Apley scratch test requires participants to attempt to touch their fists behind their backs.²³ One hand reaches down behind the neck while the other reaches up from behind the lower back. The average of the distances between attempts with the right and left hands on top was recorded as the final score.

A 30.5-cm box was used to administer the sit-and-reach test following previously described guidelines.²⁴ Participants sat with the soles of their feet flush against the surface of the box. Keeping their knees straight and hands together, they reached as far along the box as possible and held that position until the examiner counted down from 6 seconds. Testing was continued until the participant achieved the same score (± 1 cm) on 3 consecutive trials, from which the average was recorded.

Weight-bearing-lunge test procedures followed those described by Hoch et al.²⁵ A piece of measuring tape was placed perpendicular to a wall. The participant positioned his or her test foot so that it was lined up with the tape and the big toe touched the wall. The participant then incrementally moved the test foot backward from the wall and attempted to touch the wall with the ipsilateral knee while keeping the heel firmly planted. The maximum distance at which this task was successfully executed was recorded for both sides. The final weight-bearing-lunge test score was an average of the left and right sides.

Strength

Although 1-repetition–maximum lifts are the criterion standard for strength measurement, such tests were not appropriate in this investigation for reasons related to safety²⁶ and reliability.²⁷ Accordingly, we administered tests that closely estimate 1-repetition–maximum lifting capacity and can be performed safely and reliably by untrained populations. Participants were allowed to complete warm-up trials of the strength measures before data were recorded.

Modified YMCA Bench-Press Test

The YMCA (Young Men's Christian Association) bench-press test is a paced, maximal-repetitions bench press with a fixed load assigned according to the participant's sex. Men performed the test with a load of 36.4 kg (80 lb) and women with a load of 15.9 kg (35 lb).²⁶ Participants synchronized their repetitions to a metronome set to 60

beats per minute. Each beat corresponded to one-half of a repetition (either lifting or lowering), resulting in a cadence of 30 presses per minute. The test was terminated when the participant was unable to maintain this pace. The number of repetitions performed was recorded as the final score.²⁶

Countermovement-Jump Peak Power

Countermovement-jump peak power, derived from a vertical ground reaction force signal, is an excellent predictor of 1-repetition–maximum back-squat capacity.²⁸ After familiarization, participants completed 3 test trials. Each test trial was a distinct effort to jump as high as possible, followed by approximately 1 minute of rest. Participants were allotted 1 practice trial and 2 test trials, with a minimum rest of 60 seconds between efforts. They held their hands on their hips while standing quietly on a force plate (model 4060-NC; Bertec Corp, Columbus, OH). They were instructed to maintain the hands-on-hips position and complete a quick countermovement followed by a maximum-height vertical leap. Vertical ground reaction force data were collected beginning 1 second before the countermovement, as identified online by a falling threshold trigger. The signal was captured at 1000 Hz and low-pass filtered at 40 Hz. A vertical center-of-mass velocity time series was calculated via forward dynamics with the assumption that initial velocity was zero.²⁹ The force and velocity time-series data were multiplied to create a power time series. The peak of the preflight concentric movement phase from the best of 2 trials was then identified and used for analysis.

Cyclic Deep Squat, Hurdle Step, and In-Line Lunge

Dynamical postural control was assessed using force-plate signals sampled during cyclical movement behaviors adapted from common clinical screening practices. Note: although observer-based rating scales exist for these movements, no human rater scores were assigned during testing or used for analysis.

After familiarization, participants performed each test for 5 continuous repetitions, once with and once without an 18.10-kg weight vest. The testing conditions were administered in randomized order. Participants were instructed to move through a complete range of motion with each repetition of the test while adhering to standard verbal cues. Aside from completing each trial in less than 30 seconds, the only instructions provided regarding cadence were to complete the repetitions at a comfortable, self-selected pace. The purpose of this approach was to avoid introducing artificial time-domain constraints, which can substantially influence the complexity and entropy outcomes described in the next section.³⁰ Ground reaction force data were sampled at 1000 Hz with the 4060-NC force plate (Bertec Corp) and used to calculate the COP time series in The MotionMonitor software (Innovative Sports Training, Inc, Chicago, IL) for each trial.

For the deep squat, participants were positioned horizontally such that both feet were within the boundaries of the force plate. Feet were placed shoulder-width apart and parallel. Holding a dowel directly overhead with the arms fully extended, the participant proceeded to squat as deeply as possible for 5 repetitions while maintaining heel contact with the force plate.

The hurdle step was performed with an elastic hurdle set to the height of the participant's tibial tuberosity and placed across the center of the force plate along its short axis. The base of the hurdle was slightly raised to prevent any contact with the plate. Beginning with feet together and toes just shy of touching the hurdle, participants were instructed to step over the hurdle and gently touch the plate on the opposite side 5 times while holding a dowel across the back. Space on the plate was sufficient to contain each participant's entire base of support in double-legged stance while still allowing room for the heel of the working leg to touch down within the borders of the plate on the far side of the hurdle.

Lastly, the in-line lunge test—not to be confused with the weight-bearing-lunge test—was performed with the front foot positioned in the center of the plate. The toes of the participant's back foot were placed in line behind the front heel by a distance equal to the height of the tibial tuberosity when standing. Participants were instructed to perform 5 lunges while holding a dowel along the spine, each time contacting the plate gently with their back knee on a towel that had been placed just behind the front heel.

Signal Processing and Analysis of Cyclic Movements

Force-plate signals for the cyclic deep-squat, hurdle-step, and in-line-lunge tests were programmatically truncated based on vertical ground reaction force thresholds that were used to identify the completion of 5 repetitions. The truncated 2-dimensional COP time series were down-sampled to 100 Hz and low-pass filtered at 12 Hz to form the signals on which our outcomes were based. These outcomes were (1) multivariate multiscale entropy (MMSE) complexity index (MMSE_{CI}, described in the next paragraph) and (2) coefficient of variation (CV).

Although entropy metrics are common in postural-control research,³¹ special concerns had to be addressed for the present study. A full discussion of the merits of 1 entropy outcome over another is beyond the scope of this article; however, we note that the entropy metric used here was developed in part to overcome the limitations of the sample entropy algorithm³² that relate to nonstationarity and singular timescales.³⁰ Each of these is important in attempting to characterize the complexity of cyclic movement behaviors over relatively few repetitions. We followed the methods described by Ahmed et al.,³⁰ who proposed multivariate empirical mode decomposition to identify a signal's intrinsic timescales. Multivariate multiscale entropy is calculated using each of the identified timescales and then summed into the MMSE_{CI}. Because the methods associated with these entropy outcomes are rather involved, we also sought to determine whether our complexity results could be approximated using more accessible measures. Therefore, the CV of the resultant COP time series for each cyclical movement task was also analyzed.

Statistical Analysis

One-tailed dependent *t* tests were used to confirm the effect of condition on MMSE_{CI}, represented by the summation of MMSE values across all timescales derived from the same trial, and CV. In the case of MMSE_{CI}, a

higher number is interpreted to be better; in the case of CV, a lower number is better.

Multiple linear regression models were selected using group lasso penalization with a varying-coefficients structure as described by Hess et al.³³ The penalty parameter (λ) was determined based on minimum cross-validation error. The resulting models were interpreted to reflect (1) main effects of the balance, range-of-motion, and strength covariates and (2) the interaction of these covariates with the weighted-vest (W) condition, wherein the coefficients (indicated with *W) represent the change in effect relative to the no-vest (C) baseline. All balance, range-of-motion, and strength variables were hypothesized to have beneficial effects on the MMSE_{CI} and CV of the cyclical movement tasks. Two of these variables—the Apley scratch test and mean CP_V—are inversely related to their underlying constructs. Therefore, the signs of their coefficients should be opposite the signs of the others in any given model. Height, mass, sex, and age were included as nuisance variables and forced into the final models. Statistical computations for this investigation were performed in R (The R Foundation, Vienna University of Economics and Business, Vienna, Austria) using the base and *grpreg*³⁴ packages.

RESULTS

The results of 1-sided tests of mean differences in MMSE_{CI} ($C - W > 0$) and CV for the cyclical movement behavior tasks are shown in Table 1. For all tasks, the complexity index was lower in the W condition than in the C condition. An increase ($C < W$) in CV was observed in the nondominant-limb in-line lunge only. The relationship between MMSE and timescales for both conditions can be seen in Figures 1 through 5. Note that the empirical mode decomposition algorithm iterates until a predefined stoppage criterion is reached. In our analysis, the greatest number of timescales present across all trials was 9; therefore, 9 timescales were used to calculate the complexity index.

Summary statistics for each regression model are presented in Table 2. With 2 exceptions, all models were significant. The first exception was the dominant-limb in-line-lunge complexity index, for which no predictors were retained and therefore no analysis was performed. The second exception was the deep-squat CV, which did not reach the significance threshold. Proportions of variance ranged from 0.24 to 0.38 in the complexity index models and from 0.00 to 0.18 in the CV models.

The order in which variables were retained in a given model as the penalty parameter was adjusted from a maximum value, under which all coefficients were shrunk to zero, to the value at which the final variable was retained is presented in Tables 3 (MMSE_{CI} models) and 4 (CV models). The coefficient values and their respective significance test results are illustrated in Table 5.

Nuisance Variables

With respect to the nuisance covariates, no significant interaction (ie, condition-specific) effects were observed for any outcome. Age predicted a lower MMSE_{CI} in the deep-squat and dominant-limb hurdle-step tests, mass predicted a lower MMSE_{CI} in all models, and female sex was

Table 1. Descriptive Data and Paired Differences for Cyclical-Movement Task Multivariate Multiscale Sample Entropy Complexity Index and Coefficient of Variation

Test	Multivariate Multiscale Sample Entropy Complexity Index				Coefficient of Variation			
	Control Condition, Mean \pm SD		Weighted-Vest Condition, Mean \pm SD		Control Condition, Mean \pm SD		Weighted-Vest Condition, Mean \pm SD	
	Mean \pm SD	Difference	t_{49} Value ^a	<i>P</i> Value	Mean \pm SD	Difference	t_{49} Value ^a	<i>P</i> Value
Deep squat	11.76 \pm 1.64	0.82	3.17	.001 ^b	0.72 \pm 0.19	-0.02	-0.65	.26
Nondominant-limb hurdle step	11.71 \pm 1.06	0.72	4.68	<.001 ^b	1.32 \pm 0.65	0.09	1.09	.86
Dominant-limb hurdle step	11.76 \pm 1.08	0.77	5.21	<.001 ^b	1.30 \pm 0.60	0.16	1.80	.96
Nondominant-limb in-line lunge	14.96 \pm 1.59	0.82	3.33	<.001 ^b	0.91 \pm 0.45	-0.08	-1.68	.049 ^b
Dominant-limb in-line lunge	14.23 \pm 1.64	0.81	3.68	<.001 ^b	0.98 \pm 0.46	-0.05	-0.92	.18

^a Paired *t* tests for mean differences of multivariate multiscale sample entropy complexity index and coefficient of variation (alternative hypothesis: control condition > weighted-vest condition > 0).

^b Indicates difference ($P < .05$).

associated with a higher $MMSE_{CI}$ in the deep squat. For CV, height predicted a lower CV in the nondominant-limb in-line-lunge model and both hurdle-step models. In contrast, mass was associated with a higher CV in all movements except the deep squat. Finally, sex predicted a lower CV in the dominant-limb in-line lunge.

Balance Variables

A higher resultant CP_V was associated with a greater $MMSE_{CI}$ in the nondominant-limb hurdle-step test.

Range-of-Motion Variables

Greater dorsiflexion range of motion predicted higher $MMSE_{CI}$ in the deep squat and the dominant-limb hurdle step. A condition-specific effect was observed in the case of the sit-and-reach test, for which greater range of motion was associated with lower $MMSE_{CI}$ only in the W deep squat.

Greater dorsiflexion range of motion was associated with lower CV in the dominant-limb hurdle-step and in-line-lunge tests, as well as lower nondominant-limb hurdle-step CV in the W condition specifically. Lastly, greater range of motion on the Apley scratch test was associated with higher CV in the dominant-limb hurdle-step test.

Strength Variables

Significant effects related to strength covariates were not observed.

DISCUSSION

As expected, multivariate empirical mode decomposition-enhanced $MMSE_{CI}$ during dynamical postural-control tasks decreased when those tasks were performed with an external load. Although not the primary purpose of this study, this novel finding may have implications for load carriage in tactical occupations. Similar changes were generally not observed in the CVs, perhaps suggesting that structure-of-variability metrics are more sensitive to the behavioral changes we would expect to observe with an external load. Relatively few effects related to our covariates of interest reached the threshold for statistical significance, and even fewer of these effects were specific to the W condition. Therefore, evidence in support of our effect-modification hypothesis was limited.

With respect to main effects, the pattern suggested that certain covariates related to range of motion, and to a lesser extent balance, were relevant contributors to the cyclic movement behaviors tested. For both $MMSE_{CI}$ and CV, 3 of the 4 models presented in Table 5 feature significant effects related to range of motion. Additionally, our balance predictor was selected in 2 of the $MMSE_{CI}$ models and reached significance in the nondominant-limb hurdle-step test. The balance predictor in question—resultant CP_V —showed an opposite effect than we hypothesized. That is, a higher $MMSE_{CI}$ was predicted by a higher CP_V , which is traditionally considered to indicate poorer balance. Acknowledging the discrepancy with our a priori expectations, we note that this is the second such observation from our laboratory (S.M.G. et

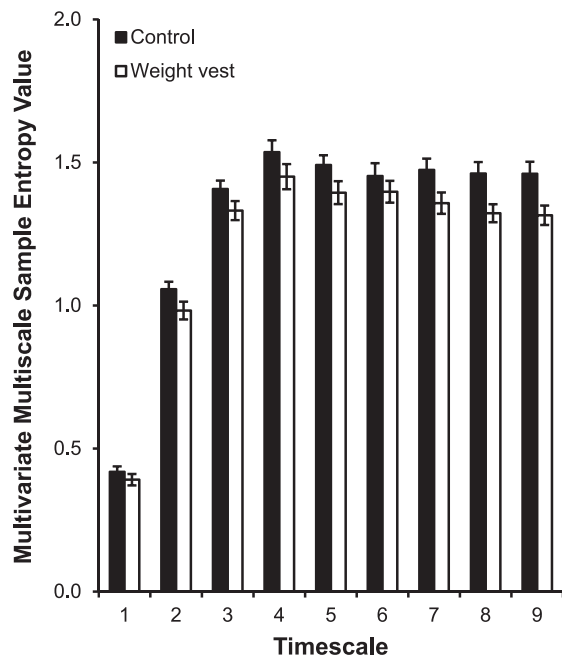


Figure 1. Deep-squat multivariate multiscale sample entropy value for each intrinsic timescale.

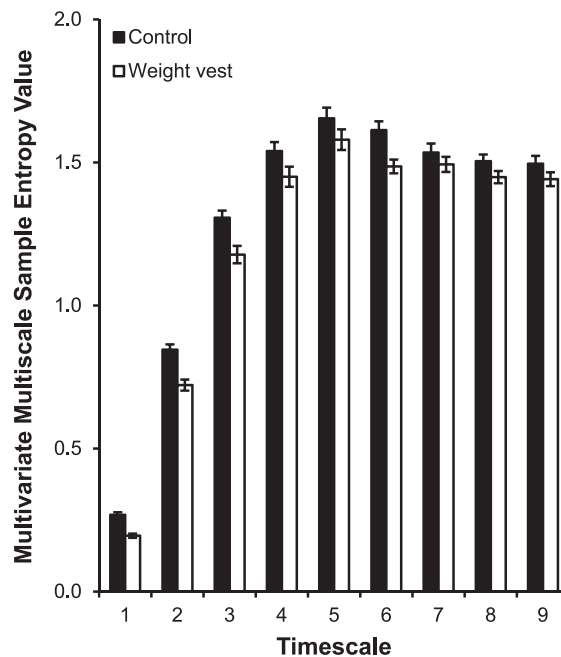


Figure 3. Dominant-limb hurdle-step multivariate multiscale sample entropy value for each intrinsic timescale.

al, unpublished data, 2015).²² The first was regarded as spurious and possibly a consequence of the protocol (double-legged quiet standing) or small sample size. In light of the current finding, future work may be necessary in which CP_V is considered for its potential as a mechanism of exploration in this balance task and for this population.^{35,36}

Complexity metrics are not always entirely straightforward in their meaning, particularly concerning which direction of movement should be considered to represent a positive or negative outcome. Results such as those we present here, in which the hypothesized effects on

complexity were not consistently supported, underscore the necessity of including treatment or group differences that can clarify the meaning of any observed changes. In our data, the MMSE_{CI} was lower in the W condition than in the C condition for all movement tests. These findings are consistent with other research in which complexity decreased as the system under observation became relatively more constrained, for example by aging or the difficulty of the task.^{30,37} (Recurrence quantification analysis entropy and sample entropy are inversely related.³¹) Combining these observations with the generally

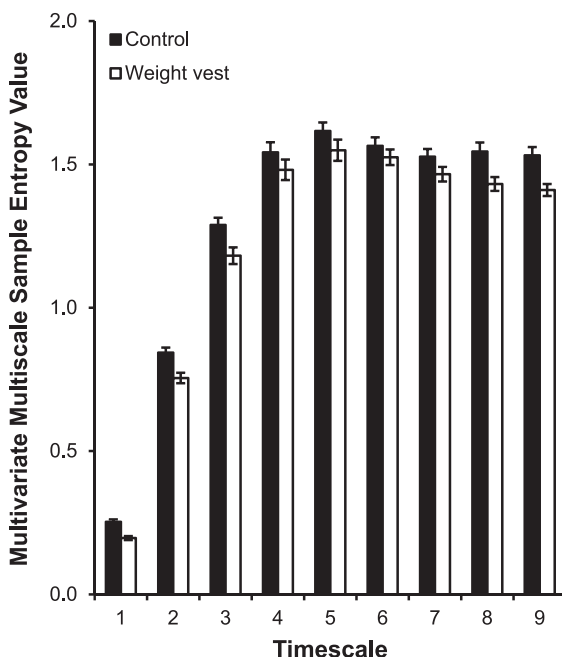


Figure 2. Nondominant-limb hurdle-step multivariate multiscale sample entropy value for each intrinsic timescale.

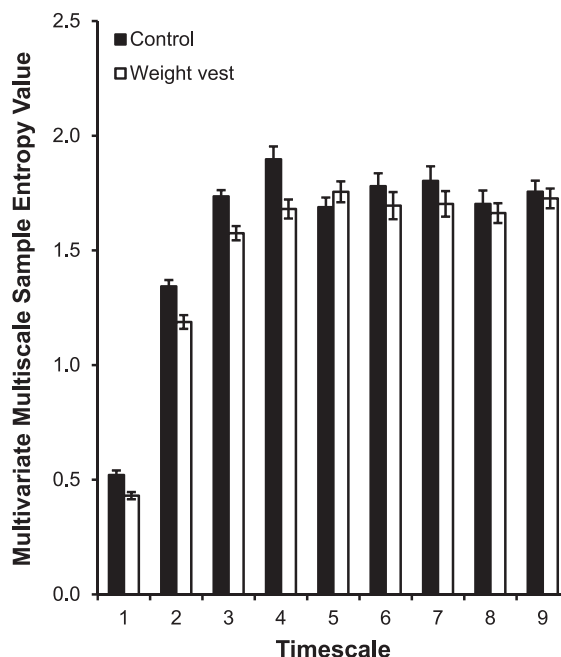


Figure 4. Nondominant-limb in-line-lunge multivariate multiscale sample entropy value for each intrinsic timescale.

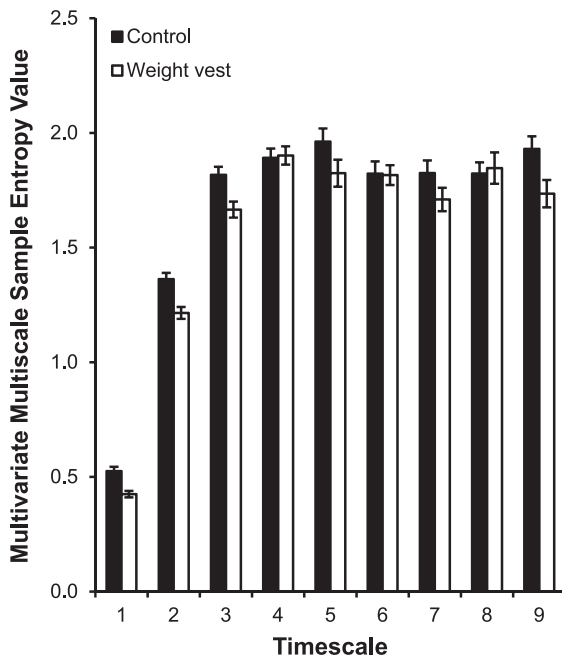


Figure 5. Dominant-limb in-line-lunge multivariate multiscale sample entropy value for each intrinsic timescale.

negative influences of age and mass, it is reasonable to conclude that the load-related decreases in the $MMSE_{CI}$ most likely reflected a less complex, less adaptable pattern of postural control.

Having established the meaning of the directionality of $MMSE_{CI}$, we can make a case for promoting the attributes we observed as unambiguous in their effects. In our results, this would include (1) dorsiflexion range of motion, which is associated with beneficial $MMSE_{CI}$ outcomes on the deep squat and dominant-limb hurdle step, as well as beneficial CV outcomes on the hurdle step and dominant-limb in-line lunge; (2) scapulothoracic range of motion, which is associated with beneficial CV outcomes on the dominant-limb hurdle step; and (3) hip- and trunk-flexion range of motion, which is associated with beneficial $MMSE_{CI}$ outcomes on the deep squat.

Two remaining observations bear mentioning. First, which attributes are most important for supporting movement depends on the movement in question. This should not be taken as disproving the existence of objectively optimal movement patterns, but it does suggest that part of the variation in movement performance can be explained by traits that are considered to represent

independent constructs,³⁸ regardless of whether *performance* refers to linear (CV) or nonlinear ($MMSE_{CI}$) outcomes. Second, separate indicators of what are traditionally considered to be “good” traits can have diverging effects on both $MMSE_{CI}$ and CV. For instance, the deep-squat $MMSE_{CI}$ is positively influenced by dorsiflexion range of motion and negatively influenced by sit-and-reach range of motion. It may therefore be the case that the dimensions of physical performance can be further divided into independent subcomponents.

One important limitation regarding the present study is that our methods manipulated constraints through a limited range of possibilities. Because the behavior of a complex system is not confined to linear changes as a function of its inputs, a more complete topological map requires a rigorous approach in which constraints are manipulated through a wide range of configurations.^{13,39} Practical limitations—fatigue, most importantly—prevented us from testing our hypotheses under a comprehensive range of conditions. As another limitation, we note that although our sample was demographically similar to tactical professional populations, our participants differed in levels of training and experience. This may limit the generalizability of our findings to experienced tactical professionals to the extent that their experience influenced the tested movement behaviors. Finally, we acknowledge that our findings should not necessarily be generalized to other types of movements or postures, particularly those in which the task itself involves unique constraints on movement performance. Many tactical behaviors (shooting, for example) meet this definition and are likely characterized by a specific variability signature.

Our findings indicate that standardized external loading was associated with decreased multiscale complexity during commonly used clinical assessments of functional movement. These changes may occur without corresponding differences in linear summary measures of variability. Additionally, we found modest evidence to suggest that balance affected $MMSE_{CI}$ and that range of motion affected both $MMSE_{CI}$ and CV. With the exception of the deep-squat $MMSE_{CI}$ and nondominant-limb hurdle-step CV, no evidence supported modification of the load effect.

CONCLUSIONS

The observed relationships could have important implications for current approaches to assessment and training of movement quality, in which functional norms are most often defined based on the medical model. Intervening in

Table 2. Penalization and Final Model Summary Statistics for Cyclical-Movement Task Multivariate Multiscale Sample Entropy Complexity Index and Coefficient of Variation

Test	Multivariate Multiscale Sample Entropy Complexity Index					Coefficient of Variation				
	Λ	F Value	Degrees of Freedom	P Value	R^2 Value	Λ	F Value	Degrees of Freedom	P Value	R^2 Value
Deep squat	0.134	5.57	7,92	<.001 ^a	0.24	0.031	1.06	6,93	.39	0.00
Nondominant-limb hurdle step	0.123	8.54	8,91	<.001 ^a	0.38	0.088	3.98	5,94	.003 ^a	0.13
Dominant-limb hurdle step	0.109	9.37	7,92	<.001 ^a	0.37	0.051	4.14	7,92	<.001 ^a	0.18
Nondominant-limb in-line lunge	0.202	8.60	6,93	<.001 ^a	0.32	0.055	2.62	5,94	.03 ^a	0.08
Dominant-limb in-line lunge	0.155	NA	NA	NA	NA	0.071	4.37	5,94	.001 ^a	0.15

Abbreviation: NA, not applicable.

^a Indicates difference ($P < .05$).

Table 3. Variable Selection Order as a Function of Δ for Multivariate Multiscale Sample Entropy Complexity Index Models^a

Rank	Deep Squat	Nondominant-Limb Hurdle Step	Dominant-Limb Hurdle Step	In-Line Lunge	Dominant-Limb In-Line Lunge
1	Age ^b	Age ^b	Age ^b	Age ^b	Age
1	Height ^b	Height ^b	Height ^b	Height ^b	Height
1	Sex ^b	Sex ^b	Sex ^b	Sex ^b	Sex
1	Mass ^b	Mass ^b	Mass ^b	Weight-bearing-lunge test × weighted-vest condition ^b	Mass
5	Sit-and-reach test × weighted-vest condition ^b	Age × weighted-vest condition ^b	Sit-and-reach test × weighted-vest condition ^b	Mass ^b	Sit-and-reach test × weighted-vest condition
6	Weight-bearing-lunge test ^b	YMCA bench-press test × weighted-vest condition ^b	Weight-bearing-lunge test ^b	Age × weighted-vest condition ^b	Resultant center-of-pressure velocity
7	Resultant center-of-pressure velocity ^b	Resultant center-of-pressure velocity ^b	YMCA bench-press test	Apley scratch test × weighted-vest condition	YMCA bench-press test
8	Apley scratch test	Apley scratch test × weighted-vest condition ^b	Resultant center-of-pressure velocity	Weight-bearing-lunge test	Weight-bearing-lunge test
9	Sit-and-reach test	Weight-bearing-lunge test	Apley scratch test × weighted-vest condition	Sit-and-reach test	Sit-and-reach test
10	Resultant center-of-pressure velocity × weighted-vest condition	Sit-and-reach test	Counter movement jump × weighted-vest condition ^c	Resultant center-of-pressure velocity	Apley scratch test × weighted-vest condition ^c
11	YMCA bench-press test	Counter movement jump	Sit-and-reach test ^c	Apley scratch test ^c	Counter movement jump ^c
12	Mass × weighted-vest condition	Apley scratch test	Counter movement jump	Resultant center-of-pressure velocity × weighted-vest condition ^c	Weight-bearing-lunge test × weighted-vest condition ^c
13	Counter movement jump	Resultant center-of-pressure velocity × weighted-vest condition	Mass × weighted-vest condition ^b	Counter movement jump × weighted-vest condition ^d	Intercept × weighted-vest condition
14	Weight-bearing-lunge test × weighted-vest condition	Weight-bearing-lunge test × weighted-vest condition	Resultant center-of-pressure velocity × weighted-vest condition	Mass × weighted-vest condition ^d	Apley scratch test
15	Sex × weighted-vest condition	Counter movement jump × weighted-vest condition	Sex × weighted-vest condition	YMCA bench-press test × weighted-vest condition	Counter movement jump × weighted-vest condition ^d
16	YMCA bench-press test × weighted-vest condition	Sit-and-reach test × weighted-vest condition	Apley scratch test	Sit-and-reach test × weighted-vest condition	Resultant center-of-pressure velocity × weighted-vest condition ^d
17	Intercept × weighted-vest condition	YMCA bench-press test	Age × weighted-vest condition ^d	Counter movement jump	Age × weighted-vest condition ^e
18	Age × weighted-vest condition	Sex × weighted-vest condition	Weight-bearing-lunge test × weighted-vest condition ^d	Sex × weighted-vest condition	YMCA bench-press test × weighted-vest condition ^e
19	Apley scratch test × weighted-vest condition	Height × weighted-vest condition	YMCA bench-press test × weighted-vest condition ^d	YMCA bench-press test	Sex × weighted-vest condition
20	Counter movement jump × weighted-vest condition	Mass × weighted-vest condition	Height × weighted-vest condition ^e	Intercept × weighted-vest condition	Height × weighted-vest condition
21	Height × weighted-vest condition	Intercept × weighted-vest condition	Intercept × weighted-vest condition ^e	Height × weighted-vest condition	Mass × weighted-vest condition

Abbreviation: YMCA, Young Men's Christian Association.

^a Relative importance of covariates is shown as a function of increasing the penalty parameter (λ). The nuisance variables (age, sex, height, and mass) were not penalized; therefore, they are present in all models.

^b Variable was selected in the final model. Variables that were selected but do not appear in Table 5 did not reach statistical significance in their coefficients.

^c Variables that share this superscript were selected in the same iteration.

^d Variables that share this superscript were selected in the same iteration.

^e Variables that share this superscript were selected in the same iteration.

Table 4. Variable Selection Order as a Function of Δ for Coefficient of Variance Models^a

Rank	Deep Squat	Nondominant-Limb Hurdle Step	Dominant-Limb Hurdle Step	Nondominant-Limb In-Line Lunge	Dominant-Limb In-Line Lunge
1	Age ^b	Age ^b	Age ^b	Age ^b	Age ^b
1	Height ^b	Height ^b	Height ^b	Height ^b	Height ^b
1	Sex ^b	Sex ^b	Sex ^b	Sex ^b	Sex ^b
1	Mass ^b	Mass ^b	Mass ^b	Mass ^b	Mass ^b
5	Resultant center-of-pressure velocity ^{b,c}	Weight-bearing-lunge test	Apley scratch test ^b	YMCA bench-press test ^b	Weight-bearing-lunge test ^b
6	Weight-bearing-lunge test ^{b,c}	Mass × weighted-vest condition	Weight-bearing-lunge test ^b	Weight-bearing-lunge test	Apley scratch test × weighted-vest condition
7	Apley scratch test	Weight-bearing-lunge test × weighted-vest condition ^b	YMCA bench-press test ^b	Sex × weighted-vest condition	YMCA bench-press test
8	Countermovement jump × weighted-vest condition	Apley scratch test × weighted-vest condition ^c	Sit-and-reach test	Countermovement jump	Countermovement jump
9	YMCA bench-press test	Sit-and-reach test ^c	Age × weighted-vest condition	Apley scratch test	Apley scratch test
10	Sit-and-reach test × weighted-vest condition	Countermovement jump	Countermovement jump	Weight-bearing-lunge test × weighted-vest condition	Age × weighted-vest condition
11	Height × weighted-vest condition ^d	Sit-and-reach test × weighted-vest condition	YMCA bench-press test × weighted-vest condition	Apley scratch test × weighted-vest condition	Sit-and-reach test
12	Resultant center-of-pressure velocity × weighted-vest condition ^d	Resultant center-of-pressure velocity	Intercept × weighted-vest condition	Mass × weighted-vest condition ^c	Resultant center-of-pressure velocity × weighted-vest condition
13	Sex × weighted-vest condition	Apley scratch test ^d	Apley scratch test × weighted-vest condition ^c	YMCA bench-press test × weighted-vest condition ^c	Weight-bearing-lunge test × weighted-vest condition
14	YMCA bench-press test × weighted-vest condition	YMCA bench-press test × weighted-vest condition ^d	Sex × weighted-vest condition ^c	Sit-and-reach test	Resultant center-of-pressure velocity
15	Apley scratch test × weighted-vest condition ^e	Sex × weighted-vest condition	Resultant center-of-pressure velocity	Intercept × weighted-vest condition	Countermovement jump × weighted-vest condition ^c
16	Sit-and-reach test ^e	Countermovement jump × weighted-vest condition	Weight-bearing-lunge test × weighted-vest condition	Resultant center-of-pressure velocity	Sex × weighted-vest condition × weighted-vest condition ^c
17	Age × weighted-vest condition ^f	Resultant center-of-pressure velocity × weighted-vest condition	Countermovement jump × weighted-vest condition ^d	Countermovement jump × weighted-vest condition	YMCA bench-press test × weighted-vest condition
18	Weight-bearing-lunge test × weighted-vest condition ^f	Height × weighted-vest condition	Resultant center-of-pressure velocity × weighted-vest condition ^d	Sit-and-reach test × weighted-vest condition	Sit-and-reach test × weighted-vest condition
19	Countermovement jump	YMCA bench-press test	Sit-and-reach test × weighted-vest condition ^d	Height × weighted-vest condition	Mass × weighted-vest condition
20	Mass × weighted-vest condition	Intercept × weighted-vest condition	Height × weighted-vest condition	Age × weighted-vest condition	Intercept × weighted-vest condition
21	Intercept × weighted-vest condition	Age × weighted-vest condition	Mass × weighted-vest condition	Resultant center-of-pressure velocity × weighted-vest condition	Height × weighted-vest condition

Abbreviation: YMCA, Young Men's Christian Association.

^a Relative importance of covariates is shown as a function of increasing the penalty parameter (λ). The nuisance variables (age, sex, height, and mass) were not penalized; therefore, they are present in all models.

^b Variable was selected in the final model. Variables that were selected but do not appear in Table 5 did not reach statistical significance in their coefficients.

^c Variables that share this superscript were selected in the same iteration.

^d Variables that share this superscript were selected in the same iteration.

^e Variables that share this superscript were selected in the same iteration.

^f Variables that share this superscript were selected in the same iteration.

Table 5. Coefficients for Multivariate Multiscale Sample Entropy Complexity Index and Coefficient of Variation in Cyclic Movement Task Models^a

Test	Multivariate Multiscale Sample Entropy Complexity Index				Coefficient of Variation			
	Variable	Coefficient	t Value	P Value	Variable	Coefficient	t Value	P Value
Deep squat	(Intercept)	13.11	4.96	<.001 ^b	Model not different			
	Age	-0.15	-2.79	.006 ^b				
	Mass	-0.03	-2.00	.049 ^b				
	Weight-bearing-lunge test	0.09	2.30	.02 ^b				
	Sit-and-reach test × weighted-vest condition	-0.03	-3.53	<.001 ^b				
Nondominant-limb hurdle step	(Intercept)	11.59	6.71	<.001 ^b	(Intercept)	3.30	3.48	<.001 ^b
	Mass	-0.04	-4.12	<.001 ^b	Height	-0.02	-2.72	.008 ^b
	Resultant center-of-pressure velocity	0.15	2.00	.049 ^b	Mass	0.02	3.37	.001 ^b
					Weight-bearing-lunge test × weighted-vest condition	-0.02	-1.96	.049 ^b
Dominant-limb hurdle step	(Intercept)	14.73	8.25	.01 ^b	(Intercept)	2.68	2.89	.005 ^b
	Sex	0.51	2.04	.04 ^b	Height	-0.01	-2.13	.04 ^b
	Age	-0.08	-2.27	.03 ^b	Mass	0.02	3.03	.003 ^b
	Mass	-0.04	-4.50	<.001 ^b	Weight-bearing-lunge test	-0.03	-2.09	.04 ^b
	Weight-bearing-lunge test	0.05	2.02	.049 ^b	Apley scratch test	-0.02	-2.62	.01 ^b
Nondominant-limb in-line lunge	(Intercept)	14.05	5.66	<.001 ^b	(Intercept)	2.25	2.81	.006 ^b
	Mass	-0.08	-5.66	<.001 ^b	Height	-0.01	-2.39	.02 ^b
Dominant-limb in-line lunge	No model selected				Mass	0.02	3.26	.002 ^b
					(Intercept)	1.63	2.06	.04 ^b
					Sex	-0.29	-2.53	.01 ^b
					Mass	0.02	3.61	<.001 ^a
					Weight-bearing-lunge test	-0.03	-2.30	.02 ^a

^a Predictor coefficients and *t* statistics are presented for each model.

^b Different (*P* < .05).

the movement pattern and intervening in the dynamical complexity of the movement pattern are not necessarily mutually exclusive; however, overreliance on the movement pattern itself as a clinical target could lead to interventions that are ineffective or potentially contraindicated. For example, recommending a movement-pattern exercise that depends on a large range of motion for a relatively inflexible individual may be just as likely to encourage a novel, unintended motor behavior as it is to “teach” that individual increased range of motion.

Clinical movement-pattern assessments provide valuable and actionable information to the practitioner, particularly because clinical observation of complexity is not yet feasible. In light of our findings, we suggest that clinicians consider performance during movement screens as possibly stemming from a combination of fundamental movement patterns and optimization of movement-pattern adaptability subject to modifiable intrinsic constraints such as balance, range of motion, and strength. Thus, interventions should be considered in relation to their effects on both outcomes discussed in this work, that is, movement patterns and the dynamical complexity of the movement pattern over time. Future research is warranted to develop detailed profiles regarding the effects of such constraints on sports and strength-training movements.

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Address correspondence to Stephen M. Glass, PhD, Department of Otolaryngology, The Ohio State University, 915 Olentangy River Road, Columbus, OH 43212. Address e-mail to stephen.glass@osumc.edu.