# HANDSTAND BALANCE MOTOR CONTROL MECHANISMS

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The goal of a handstand, a fundamental skill in gymnastics, is to maintain a balanced stance by controlling center of mass (COM) position. Successful handstands predominantly use wrist torque to control the COM in the anterior-posterior (AP) plane. The aim of this study was to determine the underlying motor control mechanisms necessary to maintain a strong handstand stance through analysis of joint angle and COM position variability. Full body 3D kinematic data were collected on three competitive level gymnasts during 30 s floor handstands. Variability of joint angles were consistently higher than the center of mass, demonstrating that joints self-organize in a motor control strategy to produce torques in order to control the COM. Using multiple linear regression analysis, it was found that shoulder flexion/extension variability was the largest contributor to controlling the COM in both the medio-lateral (ML) and AP planes.

**KEY WORDS:** motor control, postural control, kinematics, gymnastics, handstand

**INTRODUCTION:** Humans develop balance control strategies in postural stances by organizing muscle contractions to create torque about joints with the goal of controlling the global variable of center of mass (COM; Horak and Macpherson, 2011). This is a stepwise system in which the nervous system must first coordinate the muscles and joints to maintain balance, a task which is complicated by linked segments creating many degrees of freedom in which a single muscular contraction influences multiple segment and joint orientations (Horak and Macpherson, 2011; Ting et al., 2009). Following this nervous system coordination of muscular contractions, torques are produced at joints to control the COM over the base of support (BOS).

The handstand is an example of a task in which a balance control strategy must be produced to maintain the inverted position. This is fundamental skill in gymnastics due to the association with more complex skills and the fact it is performed on all apparatus in both male and female gymnastics. Four joints (wrist, elbow, shoulders, and hip) are available to assist in handstand postural control strategy (Blenkinsop et al., 2017). In organizing these joints, the nervous system is constrained by the task, environment, and specific athlete's structural and functional limitations in addition to solving musculoskeletal redundancy (Newell, 1986). Previous work has focused on the sagittal plane, in which torque about the wrist has been found to be the most prevalent control strategy (Blenkinsop et al., 2017) in a strong handstand. A strong handstand balances in a straight body line with minimal joint displacement, while weaker handstands may require compensatory torques, utilizing either a shoulder strategy or a hip strategy (Kerwin and Trewartha, 2001).

While control strategy has been determined in terms of torques required to control the COM, the underlying motor control mechanism produced by muscle and joint organization necessary to create this torque has not been established. In this step of postural control in a handstand position, muscular contractions aim to control joint angle variability to maintain the joints in angles to create a straight body line in which torque about the wrist joint can be produced. An exploration of joint angle variability during strong handstand balance can assist in an understanding of motor control strategy used by gymnasts to maintain a position in which torques can be produced to control COM position. The aim of this study was to explore motor control mechanisms of handstand balance by (1) determining the variabilities of joint angles and COM position over the course of 30 s handstands and (2) exploring which joint angular variabilities contribute to COM balance through the use of multiple linear regression models. These aims serve the purpose of increasing understanding of joint contribution to global variability in the handstand. This information will allow for accurate task decomposition and conceptual understanding of how this key skill works.

**METHODS: Participants:** Three competitive team gymnasts enrolled in the USA Gymnastics Development programme from gymnastics clubs surrounding Denver, Colorado, USA between the ages of 9-13 yrs (11±1.9 yrs) participated in this investigation. Inclusion criteria included the ability to hold a handstand for 30 seconds on both the floor and the balance beam. Gymnasts who had sustained an upper extremity injury within the past 6 months, or who currently had an injury requiring a cast on any limb were not eligible for the study.
**Apparatus:** Gymnasts were outfitted with 54 reflective markers, including a full lower and upper extremity marker set and an abbreviated head and trunk marker set. An eleven-camera passive motion capture system (Vicon Motion Systems) was used to capture full body segment motion at 100 Hz using Vicon Nexus Capture software (Motion Systems Ltd, Oxford, UK). Marker data were filtered using a $4^{th}$ order zero-phase-lag Butterworth filter with a 6 Hz cutoff frequency.
**Procedure:** Each gymnast participated in a static handstand balance pose performed for a maximum of 30 s each. The floor handstand pose reported in this work was part of a larger data collection with seven total poses, the order of which was randomized.
**Data Processing:** Local coordinate system joint angles (wrist, elbow, shoulder, hip) and COM position were calculated in Visual 3D (Version v6, C-Motion, Inc, Germantown, MD, USA). Joint angles were calculated for the left and right side of the body separately about the anterior-posterior (AP), sagittal (flexion/extension) and medio-lateral (ML), frontal (abduction/adduction) planes. COM position was calculated for both the AP and ML planes. Center of mass (COM) and joint angle variability is reported as coefficient of variation (CV) for each gymnast, as calculated in R (RStudio Version 1.2.1335). The AP and ML planes were each calculated separately.
**Statistical Analysis:** Multiple linear regression models were used to explore the relationships between COM and joint angle variability by entering ankle, knee, shoulder, and hip angles as predictor variables for COM position. Regression models were created for AP and ML COM for each gymnast separately.

**RESULTS AND DISCUSSION:** All three gymnasts held the handstand for the maximum of 30 s.

**Table 1:** Descriptive statistics (mean, standard deviation, coefficient of variation) of the COM position (m) and joint angles about the respective plane (º). Joint angle statistics were calculated for the left and right side of the body separately in each plane of motion. COM position is a global variable combining the left and right sides of the body in each plane. Results for **subject 1**, **subject 2**, and **subject 3** are color-coded.

| | Anterior/Posterior (AP) plane Extension/Flexion | | | | | | Medial/Lateral (ML) plane Abduction/Adduction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LEFT | | | RIGHT | | | LEFT | | | RIGHT | | |
| | M | SD | CV | M | SD | CV | M | SD | CV | M | SD | CV |
| Wrist | 87.99 | 2.20 | 2% | 58.16 | 2.48 | 4% | 34.07 | 1.88 | 6% | 52.93 | 1.95 | 4% |
| Elbow | 24.79 | 4.94 | 20% | 23.44 | 3.32 | 14% | 2.00 | 1.21 | 60% | 6.00 | 0.75 | 13% |
| Shoulder | 67.02 | 3.60 | 5% | 69.64 | 3.85 | 3% | 27.93 | 3.65 | 13% | 21.50 | 2.38 | 11% |
| Hip | 25.43 | 2.17 | 9% | 29.03 | 2.10 | 7% | 9.75 | 0.64 | 7% | 1.49 | 0.81 | 54% |
| Knee | 3.19 | 1.60 | 50% | 3.90 | 0.97 | 25% | 1.45 | 0.73 | 50% | 4.65 | 0.47 | 10% |
| Ankle | 29.77 | 1.12 | 4% | 22.15 | 1.02 | 5% | 0.85 | 0.86 | 101% | 1.69 | 0.83 | 49% |
| COM | 0.33 | 0.00 | 1% | | | | 0.72 | 0.01 | 1% | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wrist | 69.77 | 1.40 | 2% | 82.86 | 2.01 | 2% | 55.69 | 1.22 | 2% | 30.09 | 1.00 | 3% |
| Elbow | 31.21 | 1.90 | 6% | 26.18 | 2.71 | 10% | 13.17 | 2.29 | 17% | 12.19 | 0.89 | 7% |
| Shoulder | 66.37 | 2.76 | 4% | 70.94 | 2.52 | 2% | 32.68 | 2.68 | 8% | 25.33 | 2.16 | 9% |
| Hip | 14.36 | 0.77 | 5% | 15.56 | 0.73 | 5% | 2.00 | 0.30 | 15% | 4.98 | 0.35 | 7% |
| Knee | 0.80 | 0.63 | 78% | 3.00 | 0.66 | 22% | 2.67 | 0.24 | 9% | 1.41 | 0.30 | 21% |
| Ankle | 13.16 | 0.54 | 4% | 23.88 | 0.40 | 2% | 2.38 | 1.15 | 48% | 8.23 | 0.97 | 12% |
| COM | 0.30 | 0.01 | 2% | | | | 0.71 | 0.01 | 1% | | | |
| Wrist | 77.00 | 2.59 | 3% | 73.45 | 2.73 | 0.04 | 34.11 | 4.53 | 13% | 35.73 | 5.14 | 14% |
| Elbow | 30.16 | 4.24 | 14% | 20.95 | 6.02 | 0.29 | 3.18 | 2.18 | 68% | 6.09 | 3.01 | 49% |
| Shoulder | 66.14 | 2.39 | 4% | 75.02 | 3.55 | 0.03 | 24.88 | 7.26 | 29% | 24.78 | 8.21 | 33% |
| Hip | 27.92 | 4.04 | 14% | 27.12 | 4.51 | 0.17 | 3.69 | 0.58 | 16% | 2.16 | 0.60 | 28% |
| Knee | 9.15 | 1.27 | 14% | 7.09 | 0.75 | 0.11 | 2.03 | 0.25 | 12% | 0.99 | 0.32 | 32% |
| Ankle | 28.15 | 1.89 | 7% | 18.60 | 1.40 | 0.08 | 5.05 | 2.16 | 43% | 5.83 | 1.26 | 22% |
| COM | 0.31 | 0.00 | 2% | | | | 0.77 | 0.02 | 2% | | | |

Consistently for all three subjects, joint angle CV was higher for all joints on both sides of the body with respect to the COM (Table 1). This increased variability at joint level confirms that there are many functional degrees of freedom necessary to control the COM, and that athletes are continuously self-organizing joints to allow for a balanced posture. Table 2 summarizes the results of the multiple linear regression analyses illustrating the joint angle contribution to the global dynamic organization of the COM.

**Table 2:** Multiple linear regression analyses were run by entering wrist, elbow, shoulder, and hip joint flexion/extension and abduction/adduction angles as predictor variables for COM in the ML and AP planes. Six total regressions are reported across the two planes of motion and three gymnasts. Using standardized coefficients, joint angle variability contribution to COM position was converted to a percent. Joint angle variabilities with a contribution percent above 10% are highlighted. $R^2$ for each model (left to right, top to bottom) is: 0.82, 0.78, 0.77, 0.80, 0.69, and 0.88.

| | Medial/Lateral COM | | | | Anterior/Posterior COM | | | |
|---|---|---|---|---|---|---|---|---|
| | Extension/Flexion | | Abduction/Adduction | | Extension/Flexion | | Abduction/Adduction | |
| | LEFT | RIGHT | LEFT | RIGHT | LEFT | RIGHT | LEFT | RIGHT |
| Wrist | 5% | 3% | 3% | 0% | 0% | 4% | 4% | 6% |
| Elbow | 10% | 13% | 1% | 1% | 24% | 4% | 2% | 6% |
| Shoulder | 17% | 15% | 5% | 1% | 17% | 13% | 3% | 2% |
| Hip | 7% | 10% | 1% | 8% | 9% | 3% | 5% | 0% |
| Wrist | 11% | 12% | 9% | 1% | 9% | 4% | 5% | 7% |
| Elbow | 6% | 8% | 5% | 4% | 5% | 8% | 4% | 5% |
| Shoulder | 4% | 19% | 2% | 2% | 16% | 19% | 9% | 1% |
| Hip | 4% | 0% | 12% | 1% | 0% | 6% | 2% | 1% |
| Wrist | 5% | 6% | 2% | 1% | 4% | 7% | 5% | 4% |
| Elbow | 8% | 16% | 5% | 4% | 13% | 10% | 2% | 3% |
| Shoulder | 16% | 11% | 7% | 6% | 20% | 14% | 4% | 2% |
| Hip | 2% | 6% | 3% | 2% | 4% | 1% | 6% | 1% |

These results highlight that for the three gymnasts, shoulder flexion/extension is a major contributor to COM position. Gymnasts 1 and 3 additionally show notable contributions from the elbow flexion/extension, and Gymnast 2 has contributions from wrist flexion/extension and hip abduction/adduction. These findings highlight a within-gymnasts difference consistent with the concept of self organisation. It appears that COM in both the ML and AP planes is controlled primarily by joint flexion/extension, and joint abduction/adduction plays only a minor role in the motor control mechanism. In summing left and right joint contributions for flexion/extension and averaging across the three subjects (Figure 1), shoulder joint variability is the dominant motor control mechanism, followed by the elbow, wrist, and then hip in both the ML and AP planes. To utilize the dominant wrist strategy (Kerwin & Trewartha, 2001; Blenkinsop et al., 2017), gymnasts must self-organise joints into a straight body line. The shoulder joint appears to be the most frequently utilized joint in the organization process, indicating the importance of strengthening the shoulder joint for a strong handstand.

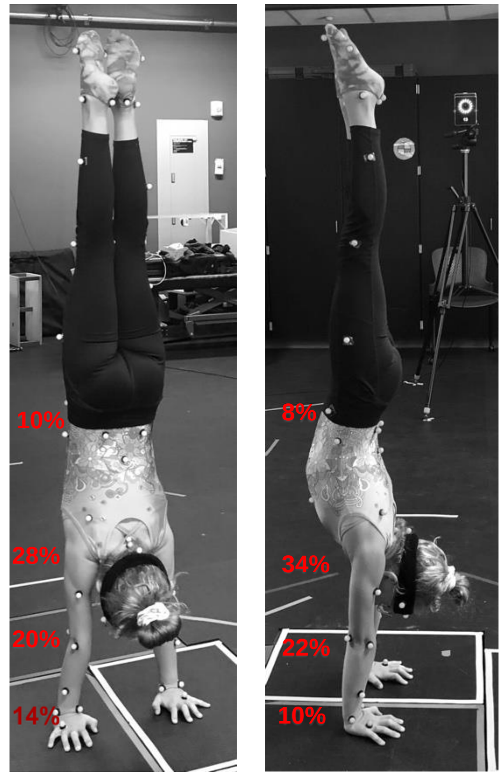


**Figure 1.** Joint angle contributions to COM position in the ML (left) and AP (right) planes are summed across the left and right sides of the body and averaged across subjects.

**CONCLUSION:** This study adds to the understanding of the underlying motor control mechanisms which control the COM in a handstand in the AP and ML plane. Joint angle variability was higher than COM variability across subjects, indicating a joint-based motor control strategy. The shoulder joint motion was predominantly related to the collective movement of COM in both the AP and ML planes. Training strategies should consider utilizing shoulder strengthening drills to improve handstand body line and balance.

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