Original Research

Kinematic Analysis of Four Plyometric Push-Up Variations

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ABSTRACT

International Journal of Exercise Science 5(4) : 334-343, 2012. Plyometric research in the upper extremity is limited, with the effects of open-chain plyometric exercises being studied most. Kinematic and ground reaction force data concerning closed-chain upper extremity plyometrics has yet to be examined. Twenty-one recreationally active male subjects performed four variations of plyometric push-ups in a counterbalanced order. These included box drop push-ups from 3.8 cm, 7.6 cm, 11.4 cm heights, and clap push-ups. Kinematics of the trunk, dominant extremity and both hands were collected to examine peak flight, elbow flexion at ground contact, elbow displacement, and hand separation. Additionally peak vertical ground reaction force was measured under the dominant extremity. The 11.4 cm and clap push-ups had significantly higher peak flight than the other variations ($P<.001$). At ground contact, the elbow was in significantly greater flexion for the 3.8 cm and clap push-up compared to the other variations ($P<.001$). The clap push-up had significantly more elbow displacement than the other variations ($P<.001$) while hand separation was not significantly different between variations ($P=.129$). Peak vertical ground reaction force was significantly greater for the clap push-ups than for all other variations ($P< .001$). Despite similar flight heights between the 11.4 cm and clap push-ups, the greater peak vertical ground reaction force and elbow displacement of the clap push-ups indicates the clap push-up is the most intense of the variations examined. Understanding the kinematic variables involved will aid in the creation of a closed chain upper-extremity plyometric progression.

KEY WORDS: Resistance training, closed kinetic chain exercise, motion analysis

INTRODUCTION

Plyometric exercise involves the use of fast eccentric loading to produce increased concentric force, also known as the stretch-shortening cycle (SSC) (12). Plyometric exercises that utilize the SSC can be used as specific training for athletes involved in sports that require fast explosive movements (4, 18). Upper extremity plyometrics have also been suggested as an integral part of terminal rehabilitation for overhead throwing athletes (4, 13, 18).

Most research concerning plyometrics has focused on the lower extremity (1). In contrast, there is a lack of research on upper extremity plyometrics (4, 11). Of the studies examining upper extremity plyometrics, many focus on open-chain exercises.

Heiderscheit et al. (9) and Schulte-Edelmann et al. (15) both utilized medicine ball throws as parts of plyometric training studies. Ballistic TheraBand (The Hygenic Corporation, Akron OH, USA) exercises and overhead medicine ball throws (2) have also been included in training studies examining the effects of plyometrics on power and shoulder internal rotator strength. Electromyography (EMG) and kinetics during medicine ball drops have also been examined with regards to plyometric effects on traditional strength training methods (5). Additionally, ballistic bench press throws (7, 11), have been utilized to examine the effects of load on kinematics and kinetics. Research concerning closed kinetic chain upper extremity plyometric exercises, specifically various types of plyometric push-ups is limited. Review articles by Wilk et al. (18), and Davies (3) suggest the use of plyometric push-ups as an upper extremity plyometric exercise but do not report any quantitative data concerning exercise intensity or progression. A training study by Vossen et al. (16) assessed the efficacy of plyometric push-ups on upper extremity power and strength measures when compared to traditional push-ups, but their use of female subjects performing push-ups from the knees does not allow for comparison to push-ups performed from the toes by males. Finally, a study by Freeman et al. (6) assessed various types of traditional and plyometric push-ups, including clap and alternating ball push-ups, mainly examining spinal loading and trunk muscle EMG during the push-up variations. While research on varying aspects of plyometric push-ups has been conducted, to date, only two studies have selectively examined kinetic or kinematic variables regarding plyometric push-ups. Garcia-Masso et al. (8) studied surface EMG and vertical ground reaction force (vGRF) of countermovement push-ups, fall push-ups, and jump push-ups in an attempt to quantify the intensity of the three variations. The authors recommend utilizing the various push-up types depending on the goal of the training session due to the musculoskeletal demands established through examination of EMG and vGRF data. Additionally, a study by Koch et al. (10) examined five characteristics of vGRF during box drop and clap push-ups. The results of this study revealed no significant differences in peak vGRF between clap push-ups and box drop push-ups from various heights.

Theoretically, a fall from a greater height would result in greater vertical forces, but as these results were not obtained by Koch et al. (10) the purpose of the present study was to examine various upper extremity kinematic variables during clap push-ups (CPU) and box drop push-ups (BD) in physically active males to potentially explain the lack of peak vGRF differences revealed in the previous study. Kinematic variables including peak flight, elbow flexion at ground contact, elbow flexion displacement, and hand separation at ground contact during CPU and BD from various heights were examined. In addition, peak vGRF was calculated under the dominant extremity. We hypothesized that peak vGRF would be similar between all conditions because of increased elbow flexion displacement as the box drop heights increased, with CPU revealing the greatest elbow flexion displacement. Additionally, we expected that peak flight height would increase as the box height increased with the CPU condition having the highest peak flight. Further, we hypothesized that elbow flexion at ground contact and hand separation would be similar between all conditions.

METHODS

Participants

Twenty-one recreationally active adult males participated in this study (24.5 ±3.7 yrs, 1.82 ± .05 m, 83.2 ± 11.7 kg). Recreationally active was defined as participating in moderate- to vigorous-intensity exercise at least three times a week, 20 minutes per session. Subjects were included in the study if they could perform four repetitions of the CPU and BD from 11.4 cm without any body part other than the hands and feet touching the ground and with minimal torso flexion or extension. All subjects were free of any upper extremity pathology or musculoskeletal injury within the past six months. Each participant received a full description of study procedures and signed an approved Armstrong Atlantic State University institutional review board informed consent document prior to study participation.

Protocol

Each subject performed the same warm up and stretching prior to testing. This included a five-minute warm up on an upper-body ergometer (Cybex Aerobic UBE, Medway, MA, USA) at a self-selected pace, as well as arm circles and a static stretch for the chest, shoulders and triceps held for 20-30 seconds each. Arm circles constitute a dynamic shoulder stretch and the static stretches were included to ensure that the involved musculature would be prepared for the high-intensity push-ups. Upon completion of the warm up and stretches, subjects were instructed on the procedures for the push-up variations. For all four variations, subjects positioned each hand on a separate force plate using a self-selected hand placement width. Additionally, for all variations, subjects started in an "up" push-up position with their hands on the force plates, their elbows fully extended, torso in a straight line, legs extended and their toes on a platform of equal height to the force plate (figure 1).

Figure 1. Starting position for all push-up variations.

BD plyometric push-ups used 3.8 cm height plyometric boxes. The boxes were placed just outside subjects' hands on each force plate. BD1 used one box (3.8 cm), BD2 used two boxes stacked (7.6 cm), and BD3 used three boxes stacked (11.4 cm) (figures 2-4).

Figure 2. BD1: 3.8 cm Box Drop Push-Up.

Figure 3. BD2: 7.6 cm Box-Drop Push-Up.

Figure 4. BD3: 11.4 cm Box-Drop Push-Up.

To perform the box drop push-ups, subjects lowered themselves towards the force plates then forcefully pushed themselves up, landing with their hands on the boxes. Subjects then pushed themselves up off the boxes and landed with their hands on the force plates. Pushing off from the plates, landing on the boxes and landing back on the plates counted as one repetition. In keeping with the explosive nature of plyometrics, subjects were not required to complete a full push-up while their hands were in contact with the boxes but instead were encouraged to flex their elbows enough to "catch" themselves, and then fully extend their elbows to push themselves off the boxes before landing on the force plates. To perform the clap push-ups (CPU), subjects lowered themselves towards the force plates then forcefully pushed themselves into the air and performed a clap before returning their hands to the separate force plates (figure 5). During the CPU, subjects were instructed to push off the force plates as explosively as possible. This protocol is consistent with directions given when instructing someone to perform these two different types of plyometric push-ups. Data collection began after subjects were given time to practice and qualitative observation of the push-ups indicated proper technique; in addition, this served as a specific warm-up for the plyometric push-ups. Kinematic and vGRF data were collected while the subjects completed four repetitions of each push-up variation (BD1, BD2, BD3, and CPU) in a counterbalanced order, resting no less than 90 seconds between variations.

Figure 5. CPU: Clap Push-Up.

Instrumentation and Data Collection: An electromagnetic tracking system (Motion Monitor, Innovative Sports Training, Inc

Chicago, IL, USA) collected (100 Hz) kinematics of the trunk, dominant elbow and both hands. Separate sensors were attached to subjects' seventh cervical vertebra's spinous process, the upper arm just distal to the deltoid insertion, the forearm (over the ulna to minimize sensor movement from forearm musculature), and to the dorsal side of both hands. During subject set-up, joint centers of the shoulder, elbow and wrists were calculated by taking midpoints between contralateral points at each respective joint using an additional electromagnetic sensor attached to a customized calibrated stylus. From the collected kinematic data, peak flight, elbow flexion at ground contact, elbow flexion displacement, and hand separation at ground contact were computed. Peak flight was calculated as the maximal vertical trunk position during push-up flight based on the position of the sensor on C7. Elbow flexion at ground contact was calculated as the angle of the elbow at ground contact. Elbow flexion displacement was calculated using the difference between elbow flexion at ground contact and peak elbow flexion. Hand separation was calculated as the distance between the hands at ground contact. vGRF data was collected (1000 Hz) using two force plates (BP400600NC 2000 Advanced Mechanical Technology, Inc., Watertown, MA, USA) with body weight normalized peak vGRF computed under the dominant extremity only. Because of the novel nature of this study, we chose to only initially examine dominant extremity kinematics and vGRF data. For the BD push-ups, kinematic and vGRF data were computed only from the push-up phase involving impact onto and propulsion from the force plates.

Statistical Analysis

The average across three trials was used for data analysis. Statistical analysis was conducted using PASW Version 18 for Windows (SPSS, Inc. Chicago, IL, USA) using separate repeated measures analysis of variance for peak flight, elbow flexion at ground contact, elbow flexion displacement, hand separation and vGRF. Bonferroni adjusted pairwise post hoc comparisons were used when indicated. Significance was set at an α level of 0.05.

RESULTS

Descriptive statistics for each variation are reported in table 1. BD3 had greater peak flight than BD2 (*P*< .001, d=.74) and BD1 (P< .001, d= 1.85). Additionally, BD2 was revealed to have significantly greater peak flight than BD1 (*P*<.001, d=1.28). Peak flight for CPU was significantly greater than both BD1 (*P*< .001, d=2.04) and BD2 (*P*= .001, d=1.01).

Elbow flexion at ground contact for BD1 was significantly greater than BD2 (*P*< .001, d=.68) and BD3 (*P*< .001, d=.84). CPU demonstrated significantly more elbow flexion at ground contact than both BD2 (*P*=.003, d=.97) and BD3 (*P*= .013, d=1.13).

CPU had significantly greater elbow flexion displacement than BD1, (P< .001, d=1.58), BD2 (*P*< .001, d=1.98), and BD3 (*P*< .001, d=1.67). No significant differences were noted for hand separation. (*P*=.129). Peak vGRF was significantly greater during CPU than BD1 (*P*= .001, d=.66), BD2 (*P*< .001, d=.53), and BD3 (*P*= .001, d=.51).

Table 1. Means ± Standard Deviations for Peak Flight, Elbow Flexion at Ground Contact (EF GC), Elbow Flexion Displacement (EF Disp), Hand Separation (Hand Sep.) and Peak Vertical Ground Reaction Force (Peak vGRF) body weight normalized.

	BD1	BD2	BD3	CPU
Peak Flight (m)	.76 ± .05	.82 ± .04[b]	.85 ± .05[a]	.87± .06[a]
EF GC (°)*	-27.03 ± 8.92[c]	-20.79 ± 9.33	-19.49 ± 8.98	-29.91± 9.40[c]
EF Disp. (°)*	-10.17 ± 5.50	-8.02 ± 4.76	-10.20 ± 4.53	-20.79 ± 7.77[d]
Hand Sep. (m)	.55 ± .09	.53 ± .06	.52 ± .08	.55 ± .08
Peak vGRF (BW)	.69 ± .11	.71 ± .12	.71± .12	.78 ± .15[d]

*Negative values indicate elbow flexion
[a] Significantly greater than BD2 and BD1
[b] Significantly greater than BD1
[c] Significantly greater than BD2 and BD3
[d] Significantly greater than BD3, BD2 and BD1

DISCUSSION

The purpose of this study was to measure various kinematic variables and peak vGRF during box drop and clap push-ups in recreationally active males. Specifically, peak flight, elbow flexion at ground contact, elbow flexion displacement, hand separation at ground contact and peak vGRF under the dominant extremity were measured during clap push-ups and box drop push-ups from 3.8 cm (BD1), 7.6 cm (BD2), and 11.4 cm (BD3) heights. The results refuted our hypothesis with regards to what we predicted would be a step-wise progression of peak flight and increased elbow flexion displacement from BD1 to CPU. Additionally, our hypothesis of similar peak vGRF and elbow flexion at ground contact between variations was also refuted. Our results supported the hypothesis that hand separation would be similar between all variations. An important outcome of this study was the relationship between peak flight, elbow flexion displacement and peak vGRF with regards to CPU. Contrary to our hypothesis, peak flight heights were not significantly different between BD3 and CPU. However, the CPU had greater elbow flexion displacement as well as significantly greater peak vGRF than all other conditions. Peak flight for CPU was 14% greater than BD1 and 6% greater than BD2; CPU elbow flexion displacement was 104%, 159% and 103% greater than BD1, BD2, and BD3. CPU peak vGRF was 13% greater than BD1 and 10% greater than both BD2 and BD3. Based on peak flight height, elbow flexion displacement and vGRF results, the CPU appears to have the greatest intensity of all conditions tested.

Peak flight during the push-up variations is related to the force exerted by the subjects to push themselves up into the air during the CPU or pushing off the boxes during BD push-ups. Our results indicate that subjects had significantly higher peak flight during the CPU and BD3 than during both BD2 and BD1. During the CPU, subjects were instructed to push-up as forcefully as possible, ensuring elbow extension. During the BD conditions, subjects were instructed to reach full extension when leaving the boxes before landing on the force plates. This was to ensure that subjects were actively pushing up and exploding off of the boxes, rather than just dropping down onto the force plates with already flexed elbows. Essentially, by requiring full extension pushing off the boxes, we hoped to establish the same relative arm position leaving the boxes between subjects and trials to accurately assess the peak flight as well as the amount of elbow flexion displacement upon landing. Based on our observations during the data collection, we expected peak flight to increase in a sequential manner from BD1 to CPU. Lack of significant differences in the flight heights of BD3 and CPU are possibly attributed to muscle power limitations. In other words, some subjects may not have had adequate ability to propel themselves to a flight height that was greater than the flight height of BD3. Further analysis of our results revealed that 7 subjects' CPU flight height was indeed lower than their BD3 flight height. Additionally, as these push-up variations were novel for most subjects, differences in motor-unit recruitment patterns or motor learning differences may have contributed to the results obtained.

Elbow flexion at ground contact was recorded as the elbow angle at initial ground contact on the force plate. Both BD1 and CPU had significantly greater elbow flexion at ground contact when compared to BD2 and BD3. This contradicts our hypothesis that all conditions would have similar elbow flexion at ground contact. This may be explained in part due to the timing required by the participant to complete the BD1 and CPU variations. The BD1 condition was the lowest height of all conditions, meaning that the subjects were closer to the force plates after leaving the boxes and therefore had less time to plan for the loading (pre-stretch) phase. Similarly, even though greater peak flight heights were achieved for the CPU, subjects had to perform a clap while in the air. The time it took during flight to perform the clap as well as return the hands to a ready position before landing may explain the greater elbow flexion at ground contact during the CPU condition. The required clap put the subjects' arms into an already elbow flexed position before landing whereas the subjects were preparing for landing in the BD conditions (specifically BD2 and BD3) with more elbow extension because no clap was required. During the BD2 and BD3 conditions, the subjects' hands began from a higher vertical position than with BD1, therefore allowing more time to ready themselves for the loading phase, which may explain why they landed with less elbow flexion.

Elbow flexion displacement during the landing phase was initially hypothesized to increase as the heights of the boxes increased, with CPU having the greatest elbow flexion displacement under the premise that a greater elbow displacement would occur to absorb the greater peak vGRF incurred after presumably falling from a greater height. Elbow flexion displacement was significantly greater during CPU compared to all the BD conditions, but contrary to our hypothesis, elbow flexion displacement was not significantly different between the three box drop conditions. This is likely attributable to the relatively small difference in height of the three boxes. Even though the box heights increased by 3.8 cm with each BD condition, the range of heights may not be large enough to elicit a change in elbow flexion displacement. BD push-ups from heights greater than 11.4 cm may require a larger elbow flexion displacement to absorb the landing impact force, but this was not tested. Interestingly, the CPU had a greater displacement than all the BD conditions, although peak flight height between CPU and BD3 was not significantly different. This is possibly explained by the instructions of the CPU versus those of BD3 to be as explosive as possible. To perform the CPU "as explosively as possible" it is possible that subjects inherently went through more elbow flexion displacement (pre-stretch) upon landing on the force plates to prepare for the subsequent concentric phase. Because subjects' were essentially aiming for a target (push up to the boxes) for BD3, it is possible they did not go through as much elbow flexion displacement to prepare for their next push-up. In other words, subjects may have allowed their elbows to flex more between CPU repetitions, creating a greater pre-stretch of the muscles and thus a more explosive push-up, whereas for BD3, the presence of a target to reach may have caused subjects to subconsciously only elbow flex "as much as needed" to successfully land the next push-up to the boxes.

Hand separation was measured to eliminate the possible confounding effect that hand separation distance may have had on elbow flexion upon landing on the force plates. Unlike the BD variations, the CPU did not require having the hands inside the boxes. Because hand separation during CPU was not constrained, we thought that a wider or narrower hand separation distance might occur and change the kinematics at the elbow for the CPU. No significant differences between the four push-up variations were noted for hand separation. The lack of significant differences is likely due to subjects self-selecting their beginning hand separation for all push-up positions. Because the subjects selected their own hand separation it is likely they chose a comfortable amount of separation and it remained consistent for all conditions including the CPU.

Peak vGRF was significantly greater during CPU than for all other conditions. This was despite similar flight height between BD3 and CPU, as well as greater elbow flexion displacement during the CPU than for all other conditions. Based on these results, the CPU condition appears to have a greater intensity than any of the box drop push-ups. Revealing a significant difference in peak vGRF contradicts a previous study by Koch et al. (10) that revealed no difference in peak vGRF between the same four push-up variations.

Based on the results of Koch et al. (10), we expected similar peak vGRF results; however, our hypothesis was not supported. Multiple factors may be responsible for the difference in peak vGRF results between our investigation and the former. First, over half of the subjects in

Koch et al. (10) study were active duty Marines who performed a variety of push-ups on a weekly basis. Our study included physically active subjects; however we did not require subjects to have extensive experience with various push-up types. We sought physically active males, with the intent to generalize results to recreational athletes or physically active males who might be required to perform plyometric push-ups as part of a rehabilitation or training program. Subjects qualified for the study based upon activity level and the researchers' qualitative analysis of the subject's ability to perform the various plyometric push-ups. Some literature focusing on lower extremity plyometrics suggest a base level of strength for the lower extremities should be attained prior to engaging in lower extremity plyometric training (14, 17) however, there is little evidence for how much strength is sufficient in the upper extremities to effectively perform plyometrics (4). We did not assess isotonic strength of our subjects and it is possible that even though our subjects were recreationally active, some may have had less than adequate strength levels necessary to effectively eccentrically decelerate during the loading phase when compared to the Marines in the previous study. This lack of strength to decelerate may have additionally impacted elbow flexion and elbow flexion displacement causing increases in both variables across the variations. Koch et al. (10) did not examine kinematic variables, so the kinematic differences between subject groups cannot be determined.

In the present study, peak vGRF was only measured under the dominant extremity. It is possible that subjects adopted an asymmetrical loading strategy during the more difficult plyometric push-up conditions. Subjects may have preferentially loaded the dominant upper extremity, which could explain the significantly different peak vGRF between BD3 and CPU conditions despite no difference in peak flight. The investigation by Koch et al.(10) revealed the dominant limb demonstrating significantly greater peak vGRF than the non-dominant across all four push-up conditions. Future research should examine kinematics and peak vGRF of both limbs.

The differing results obtained by Koch et. al (10) and those of the present study regarding peak vGRF suggest that future research is needed to increase the understanding of underlying kinematic variables of closed chain upper-extremity plyometrics. It appears that population differences may exist with regards to peak vGRF patterns. Future plyometric push-up research comparing a variety of populations may help in determining whether the differences in peak vGRF between the different variations revealed in the current study are atypical. Evaluation of kinematic data including the glenohumeral and scapulothoracic joints may also help explain variances in peak vGRF during various plyometric push-up conditions. In addition, research involving higher box drop conditions with experienced subjects could aid in the development of a step-wise progression of plyometric push-up intensity.

The purpose of this study was to assess kinematic variables and peak vGRF patterns during various plyometric push-ups in recreationally active males. Based on our results, CPU appear to be the most intense of all conditions tested, however box drop push-ups from boxes higher than 11.4 cm were not assessed in this study. Understanding the demands and intensities of various plyometric push-up variations will aid physical therapists and sports performance coaches in the prescription of these exercises in returning an athlete to play or in improving explosive upper-body power.

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