Biomechanical assessment of the connection between risk of wrist fracture and the dumbbell chest press exercise performed on an exercise ball

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Abstract: Multiple incidents of exercise balls bursting during a dumbbell chest press have been reported. This study quantified the dynamics of the dumbbell chest press performed on such balls and the force applied throughout the exercise cycle. To do so, a well-documented case was replicated using subjects of similar weight, background and athletic ability in the same dumbbell chest press motion. Subjects were instructed to perform repetitions on the exercise balls at both a self-selected pace and at maximal speed using various masses. Dynamic measurements were made to record ball loading, ball loading rate, ball compression, and kinematics of the subjects. Peak loads averaged 2084 N in the case of fast trials and 1815 N for self-selected speed trials. Biomechanical aspects of injury causation and the safe use of exercise balls are discussed throughout the products life cycle; from design and manufacturing to the conditioning professional and athlete end user.

Keywords: exercise ball; physio ball; Swiss ball; wrist; fracture; Galeazzi; equipment failure; dumbbell press; chest press; forensic; engineering.

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1 Introduction

Exercise balls are an important tool for rehabilitation and conditioning. Their popularity comes from their unstable support that requires the athlete to engage antagonistic muscles in order to increase joint stiffness and therefore joint stability to assist balance (Lander et al., 1985; Lehman et al., 2005a; Lehman et al., 2005b; Lehman et al., 2006; Marshall and Murphy, 2005; Marshall and Murphy, 2006). However, the benefits of exercise balls are accompanied by the risk of failure of the equipment. Under certain conditions, elastomer objects are susceptible to leaks and in some circumstances, bursts. These failures can have catastrophic results on an unsuspecting athlete (Consumer Product Safety Commission, 2009; James, 2010).

Ball exercises in which the athlete is required to lift or hold added mass are especially dangerous. Such exercises include dumbbell chest presses performed using exercise ball for support instead of a regular bench. This risk was recently brought to the general public’s attention when it was revealed that a high-profile professional basketball player, Francisco Garcia (National Basketball Association), suffered a wrist fracture when the exercise ball he was using suddenly deflated (James, 2010). The athlete fell to the ground with heavy dumbbells (40.8 kg each) in hand. The fall, coupled with the mass of the dumbbells, caused dislocations of the radio-ulnar joint at the wrist as well as a fracture of the radius bone, an injury medically termed a Galeazzi fracture (Hinshelwood and Caro, 2009). Witness accounts described the accident as the exercise ball catastrophically bursting as the athlete was in the middle of the “pressing” phase of a repetition. However, the manufacturer maintained that their products can only fail in a slow leak deflation manner.

Other cases of catastrophic failure leading to sudden deflation and subsequent injury have been reported (Arritola v. Ledraplastic SpA et al., 2009; Carino v. Ledraplastic SpA et al., 2006; Carter v. Ledraplastic SpA et al., 2002; Ernst v. Ledraplastic SpA et al., 2012; Fricke v. Ledraplastic SpA et al., 2010; Handy v. EXCL Spa & Fitness et al., 2013; Wheeler v. Ledraplastic SpA et al., 2002). Amongst them is another high level basketball player (National Collegiate Athletic Association) who reportedly suffered a wrist fracture performing a chest press exercise on an exercise ball when it suddenly deflated (Brockway, 2008; College Basketball Injury Report, 2008). Recognising the costs associated with injury litigation, it is likely that many other unreported incidents have occurred without leading to court proceedings. However, considering the number of reported occurrences, it remains surprising that the link between the chest press exercise and risk of wrist fracture has not been formally investigated.

For this reason, it is important to examine the dynamics of the exercise, its effects on the ball, and the conditions in which the balls are being utilised (Safe-Wise Consulting, 2012). To do so, athletes were asked to perform dumbbell chest presses on exercise balls under controlled conditions as to reconstruct the documented incidents. The movement was then broken down into quantifiable events and different conditions were examined. The data was also probed to identify conditions that increase risk of wrist injury and mitigating factors for injury prevention.

2 Methods

In order to reproduce the dynamics of the reported incidents, three surrogate male basketball players (height: 193.1–197 cm; weight: 988.8–1124.2 N (222.2–252.7 lbs); age: 21-24 yrs.) were recruited for this study. The subjects were selected from high-level basketball programs (NCAA and CIS) for their basketball skill level and conditioning regime. Each subject provided informed consent prior to performing the study.

Participants were asked to perform a dumbbell chest press with their feet on the ground and upper back resting on an exercise ball. For safety, participants were fitted with a fall arrest harness and helmet (Vertex Best Helmet, PETZL, France) in order to prevent injury in the case of failure of the exercise ball (Figure 1). Brand new exercise balls (Gymnic Plus, Ledraplastic, Italy), the same used in the Garcia incident, were inflated to specific diameters (70 and 75 cm) and used for the tests. Measurements taken during each trial included contact force of the ball against the floor, and kinematics of the subject.

A 12 camera passive marker motion capture system (Eagle, Motion Analysis Corp., Santa Rosa, CA) was used to measure kinematics using a modified Helen Hayes marker set (Collins et al., 2009) in order to extract wrist and elbow position and angle. Ball compression was also extrapolated. The calibrated volume was 5 m long x 3.5 m wide x 2.5 m high. Cortex 3.1 software was used to collect the data at 120Hz. This kinematic data was processed using a 6 hz low-pass Butterworth filter.

Forces were measured at 1200 Hz using an AMTI force plate (Model OR 6-7, Watertown, MA) embedded in the floor surface. The exercise ball was positioned as to only be in contact with the force plate. Force data was collected and synchronised with kinematic data via analog channel connections and the master camera clocking for the National Instruments data acquisition system (NI USB-6259, Austin, TX) interfaced with the Cortex software. For thoroughness, trials were also filmed using a Sony Handycam (CX760, Tokyo, Japan) digital camera.

A warm-up trial was performed with each participant executing four to ten repetitions with two 27.2 kg dumbbells. After resting for a minimum of two minutes the participants were then instructed to perform two repetitions at a self-selected pace and two repetitions at maximal speed. With assistance, masses were then exchanged for either 31.8 kg or 36.3 kg dumbbells. A total of four repetitions were recorded before increasing the dumbbell mass to 40.8 kg. This sequence was randomly performed with both the 70 and 75 cm exercise ball in order to investigate the effects of underinflation.

Figure 1 Instrumented and harnessed subject (elbow marker hidden)

Truncating the data files was necessary to normalise a chest press repetition; a single cycle was determined by identifying the highest height of the wrist at the start point and the highest height of the wrist when finishing.

Kinematic and kinetic data were grouped according to condition, normalised to the chest press cycle (0–100%) and averaged over the cycle domain. Meaning that a minimum of three data points exist for every percentage point over the cycle of each condition, depending on the conditions. This allowed a standard error to be applied to each percentage point across the cycle. Statistical analysis consisted of two-tailed t-tests of data during key points of the cycle.

3 Results

To qualitatively describe the quantitative kinematics found during the exercise, the movement cycle can be broken down into four key events. Event #1 consists in the subject holding the dumbbells with elbows extended and the mass immobile vertically above the shoulders. Event #2 occurs when the elbows initially flex and shoulders horizontally extend, allowing the dumbbells to be lowered down in a short moment of reduced acceleration due to gravity. As the dumbbells are lowered, they are gradually stopped and pushed upward as soft-tissues are passively stretched and the appropriate muscle groups are activated. Through this change in direction of the mass, the acceleration vector changes direction and reaches a maximum magnitude labelled Event #3. To conclude the cycle, Event #4 occurs as the dumbbells are roughly half way up (elbows at 90 deg) moving towards the fully extended elbow position and the masses start to decelerate. This key moment is also called the sticking point.

Figure 2 Idealised force cycling of a single dumbbell chest press repetition. Loading is expressed in terms of dumbbell mass inertial force, as their movement is the main cause of the force modulation experienced by the ball (see online version for colours)

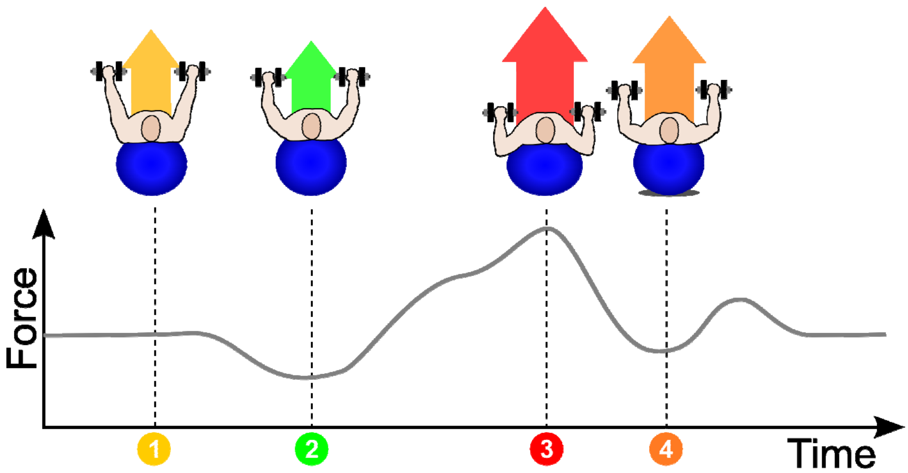


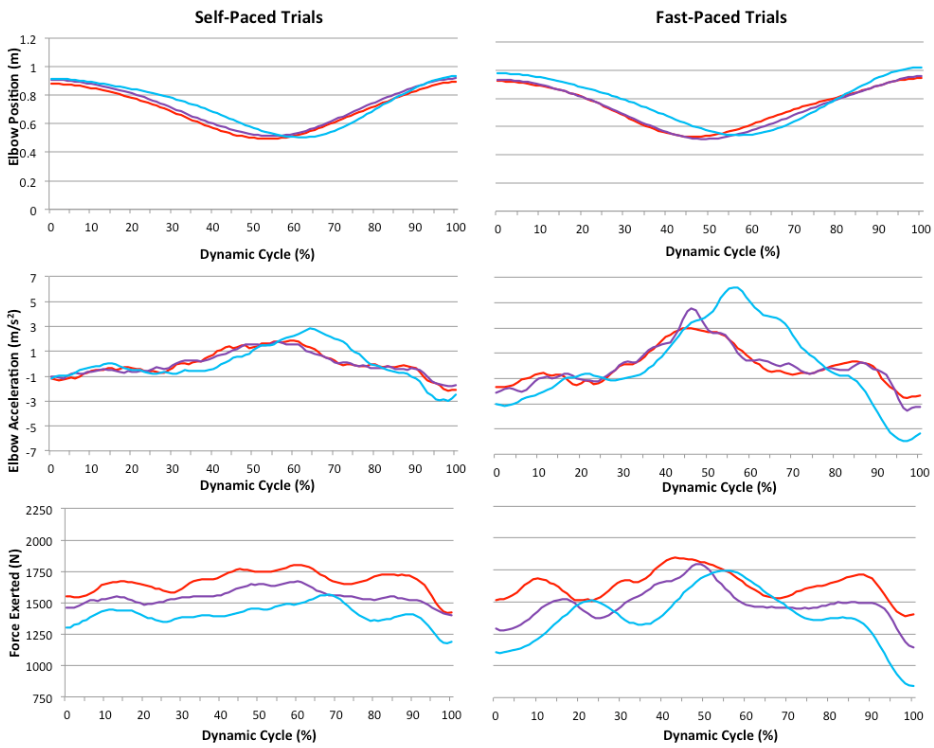
Figure 2 idealises this cycle by showing the magnitude of the force applied on the ball with respect to time as recorded on force plates as well as the key events as previously described. As can be seen in the force traces, the largest force peaks occurred at event #3, and were higher in amplitude for fast-paced trials. In the case of self-paced trails, the maximum force reached a mean ±standard deviation of 1816 ±179 N during the dumbbell turnaround at event #3, with an absolute maximum of 2145 N in one trial. Fast-paced trials showed significantly higher (p<0.05) peak at a mean ±standard deviation of 2098 ±166 N, while the absolute highest peak measured 2375 N. Meanwhile, the dip in force shown at event #2 showed lower values for fast-paced trials than self-paced trials (p>0.05). Self-paced trials had a mean ±standard deviation of at 1410 ±138 N while the fast-paced trials had a mean ±standard deviation of 1219 ±196 N. The mean percent difference between the larger dynamic peak forces of event #3 and the static forces of event #1 were over double the amount during fast-paced trials. Further, the mean percent difference between the larger dynamic peak forces of event #3 and the minimum forces of event #2 were similar across dumbbell masses in the self paced trials but were significantly negatively correlated with dumbbell mass in fast paced trials. Complete results can be consulted in Table 1.

Table 1 Mean ± standard deviation ground reaction force at key moments in the exercise cycle. Maximum dynamic load (Event #3) has also been expressed as a percentage of Static Load (Event #1) and Minimum Load (Event #2)

	Dumbbell Mass (kg)	*Event #1 Static (N)*	*Event #2 Minimum (N)*	*Event #3 Maximum (N)*	*Event #3 as % of Event #1 (%)*	*Event #3 as % of Event #2 (%)*
Self-Paced	27.2	1512 ± 155	1277 ± 87	1644 ± 126	109	129
	36.3	1613 ± 72	1411 ± 58	1795 ± 92	111	127
	40.8	1728 ± 150	1505 ± 80	1954 ± 145	113	130
	Mean	1630 ± 160	1410 ± 130	1815 ± 179	111	129
Fast-Paced	27.2	1671 ± 274	1047 ± 195	2065 ± 139	124	197
	36.3	1620 ± 84	1179 ± 103	2035 ± 122	126	173
	40.8	1780 ± 109	1359 ± 109	2129 ± 224	120	157
	Mean	1685 ± 243	1219 ± 183	2084 ± 176	124	171

Notes: Event#1: weights held immobile.
Event#2: weights are lowered.
Event#3: weights are stopped and pushed upward.

Figure 3 Mean elbow position/acceleration and mean ground reaction force calculated from each repetition of each participant for each mass condition compared between self-paced and fast-paced trials (Red: 40.8 kg; Purple: 36.3 kg; and Blue: 27.2 kg)



It should also be observed in Figure 3 that in both self-paced and fast-paced trials, the force peak appeared later in the trial for the smallest masses, although this difference was not statistically significant. At that force peak, the ball was compressed maximally, which in turn brought the elbows to their lowest position. The mean ±standard deviation for this position was 47 ±10 cm above the ground as reported in Table 2.

Table 2 Elbow height at peak force (event #3)

		Dumbbell Mass		
		27.2 kg	*36.3 kg*	*40.8 kg*
Self-Paced Under Inflated	Mean (m)	0.430	0.416	0.457
	Standard Deviation (m)	0.059	0.036	0.043
Self-Paced Properly Inflated	Mean (m)	0.418	0.396	0.462
	Standard Deviation (m)	0.056	0.055	0.038
Fast-Paced Under Inflated	Mean (m)	0.538	0.501	0.528
	Standard Deviation (m)	0.038	0.043	0.055
Fast-Paced Properly Inflated	Mean (m)	0.513	0.488	0.503
	Standard Deviation (m)	0.049	0.042	0.065

Table 3 displays the mean ±standard deviation for each of the key events as described previously. Results based on ball inflation showed no significant difference between the conditions tested ($p > 0.05$).

Table 3 Impact of ball inflation on cycle loads (mean ± standard deviation)

Product	*Ball Diameter (cm)*	*Event #1 Static (N)*	*Event #2 Minimum (N)*	*Event #3 Maximum (N)*
Under Inflated	70	1580 ±142	1030 ±206	2140 ±197
Proper Inflation	75	1575 ±126	1013 ±147	2178 ±158

Notes: Event#1: weights held immobile.
Event#2: weights are lowered.
Event#3: weights are stopped and pushed upward.

4 Discussion

In order to link the biomechanical aspects of the chest press on an elastomer ball and the risk of rupture with eventual wrist fracture, it is logical to start investigating the dynamic nature of the exercise. With self-paced trials, force peak means are distinguishable between mass conditions but percent differences are not, whereas during fast-paced trials, peak force means are similar but percent differences are distinguishable (Figure 3 and Table 1). This is likely attributed to physical limitations of power exerted by subjects (equation 1). With power, P, being the amount of work, W, that one can accomplish per unit time, T, it is likely that the force modulation, F, at larger masses is limited by the inability to perform the increased work under the same time frame as with smaller masses moved over the same distance, *D* (equation 2).

$$Power\,(P) = \frac{Work\,(W)}{Time\,(T)} \quad (1)$$

$$Work\,(W) = Force\,(F) * Distance\,(D) \quad (2)$$

This limitation of athlete's performance would therefore act as a limitation to the force modulations applied to the ball.

As the data suggests, larger masses wouldn't necessarily be more likely to cause higher loads. By examining the elbow acceleration trace for fast-paced trials, it is possible to justify the higher power output in the case of the smaller mass, which in turn increases the force transmitted to the ball and the overall force modulation magnitude. This suggests that the risk of ball failures caused by high loads does not lie solely in the use of heavy dumbbells, but in the speed of repetition execution as well. In other words, lighter dumbbells moved fast, and heavier dumbbells moved more slowly cause similar peak loads but different force modulation magnitudes throughout the exercise cycle.

However, during testing, no ball rupture was observed despite loads as high as 2407 N. At the time of Mr. Garcia's incident, the exercise ball used displayed a safe-use limit of 272 kg (2668 N). During testing, the load applied to the balls never exceeded more than 90% of this stated safe-use limit (in one trial) and averaged 68% and 78% of the stated safe-use limit in the case of self-paced and fast-paced trials respectively. These forces measured during the exercise would therefore qualify as safe according to manufacturer specifications, albeit minimally. Despite this data, the manufacturer has recently revised the product's safe-use limits to 120 kg (1,177 N) with an overall tested load capacity of 300 kg (2943 N) (Gymnic Plus Product Page, 2014).

Therefore, the cause of this incident cannot be solely attributed to the dynamic nature of the exercise since none of the tested balls failed nor did the load exceed original safe-use limits provided by the manufacturer. However, eyewitness accounts (Garcia v. M-F Athletic Company, Inc., 2012) state that the ball "burst" during or around what is defined herein as Event #3. This key moment is also where elbows are at an angle of less than 90 degrees, putting the forearms in a perpendicular position with the ground. A sudden catastrophic failure of the ball at this position would put the athlete at risk of wrist fracture. At this moment in the exercise cycle, however, ball compression is such that the athlete's elbow is approximately 42-52 cm above the ground (see Table 2).

It is also notable that the conditions necessary for Galeazzi fractures to occur include having an axial load placed on an extended and internally rotated wrist. Those two conditions are met in the case of a dumbbell chest press exercise.

Using Galeazzi fracture tolerances published by Lubahn et al. (2005) and Messerer (1880), it is possible to use this study's results to estimate if falls during the exercise would cause a wrist fracture.

By conservation of energy (neglecting air friction),

$$mgh = \frac{1}{2}mv^2 \quad (3)$$

$$\Rightarrow v = \sqrt{2gh} \quad (4)$$

The impulse of the mass's impact through the arm with the ground is given by

$$F\Delta t = m\Delta v = m(0 - v) = -mv = -m\sqrt{2gh} \tag{5}$$

where F is the average impact force, Δt is the impulse duration (time for the momentum of the mass to change from mv to 0), and Δv is the change in the dumbbells velocity on impact. Rearranging this equation leads to the formula for the drop height:

$$h = \frac{1}{2g}\left(\frac{-F\Delta t}{m}\right)^2 = \frac{g}{2}\left(\frac{-F\Delta t}{mg}\right)^2 \tag{6}$$

By substituting the values obtained from previous research (Lubahn et al., 2005; Messerer, 1880) radial bone fracture tolerances more specific to these cases (athletic males) range from 3896 N in the case of a 42 cm fall and 4448 N for a 55 cm fall. This calculation therefore suggests that this injury can likely occur from a height as low as 42 to 55 cm and that the ball rupture was nearly instantaneous. In other words, this means the ball would not have slowed the fall of the athlete after rupture thus reducing the possibility of a gradual "leak" type failure.

Free-fall calculations from this height also show the athlete would have approximately 300 ms from the moment the ball ruptured to contact with the ground. Considering average human reaction time to an auditory stimulus is about 150 ms (Kosinski, 2013), the athlete would have had approximately 150 ms to move to a safer position to absorb the impact. Considering the complexity of the decision making involved in order to fall safely in such a situation, coupled with the lack of psychological preparedness of the athlete, it is likely that the athlete's arm orientation at the time of the burst be similar to its orientation at impact with the ground.

According to this analysis, the injury incurred by Mr. Garcia and others, appears to only be possible under a catastrophic ball failure. Therefore, it is necessary to explore the factors that make the failure possible under the loads generated by the exercise. For example, prolonged use can lead to multiple types of material fatigue, which can cause stress concentrations that lead to failure (Kies et al., 2004). There is also evidence that trace elements such as copper used to colour balls may affect its ability to resist a flaw such as an abrasion or puncture (Girois, 1999). A study performed by Exova (Warren, MI) showed certain coloured balls (blue and green) ruptured catastrophically when a flaw was introduced to a statically loaded ball, while other coloured balls slowly deflated under the same conditions (unpublished data). Additionally, long-term ultraviolet radiation exposure has a history of negatively affecting mechanical properties of plastics; combined with abrasions, scratches, and acute localised pressure differentials may also be potential causes of ruptures. Micro fractures may develop over time and weaken the integrity of the product and under the right circumstances cause a catastrophic failure. Loading rate has specific effects on fracture behaviour and the fatigue processes depending on the type of material (Kabir et al., 2006; Saha et al., 2005; Hertzberg et al., 1975). While loading rate was recorded here, it was not a condition tested, therefore the issue warrants more focused discussion than can be provided here. Considering the reported cases of "sudden deflations", manufacturers would benefit from identifying and quantifying the situations where these failures are possible and either share this information with end users or prevent them at the manufacturing phase.

In the context of the reported incidents, the exercise balls were used under professional supervision. These professionals along with the end user should be aware of both the proper use and care instructions and injury trends of products used to condition clients. Manufacturers would protect end users more effectively by following "design hierarchy of controls" and "user centred design" approaches for a more safe and enjoyable product experience. Only after design considerations should manufacturers follow the ANSI Z535.4 standard for product safety signs and labels.

Finally, as the data shows, end users (athletes), conditioning professionals, and manufacturers must be aware that weighted exercises can generate much higher loads than the total static mass on the ball may suggest. Weighted exercises on inflated balls should therefore be managed carefully or reserve these exercises for a stable bench or an alternate exercise altogether. This assessment may also hold true for other un-weighted exercises with highly dynamic movements especially if performed by a heavier individual.

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