SUMMARY

Background: A vital tool in military action, the grenade is a tactical weapon for use at a distance. To provide for optimal throwing range and accuracy, the mass of the grenade must be examined. Historically, only the physical distance and accuracy to target is measured to determine the most advantageous mass of a thrown object. This neglects the effects each object has on the throwing soldier. Resultant fatigue and injury can therefore only be understood through direct measurement.

Methods: This study examined 3 soldiers as they threw 5 grenades of different mass. Each soldier utilized 3 throwing methods including; crouching before a standing throw for distance, crouching before a standing throw for accuracy, and running to a standing throw for maximum distance possible. Electromyography (EMG) was collected on 4 muscle groups and a full body 3D inertial measurement unit (IMU) system was worn to capture kinematic throwing data including anatomical angle ranges, rotational velocities, and sequence of body movements.

Results: 1. Overall muscle effort was directly proportional to the mass. 2. Shoulder range of motion was found to decrease with increased mass. 3. Specifically, external shoulder rotation was found to decrease with increasing grenade mass. 4. Compared to throwing for accuracy, when soldiers threw for distance they had higher maximum muscle activity but lower overall muscle effort spent as the high amplitude was over a short duration. 5. Throws were found to be appropriate for the open kinetic chain (OKC) principle. 6. The AFG grenade was found to have the lowest potential for shoulder injury, but further study in needed. 7. Throwing grenades with 16 ounces mass for maximum distance was found to require the least amount of total work.
INTRODUCTION

To better evaluate the impact each grenade had on the throwing soldiers, the kinematic sequence was analyzed. This kinematic sequence itself or the underlying kinetic mechanism is often called the “proximal-to-distal sequence,” “kinetic chain,” or “whip-like effect” (Atwater, 1979; Feltner, 1989; Fleisig et al., 1996a; Kibler, 1995). While data was collected on the entire body, only those arm segments involved in the Open Kinetic Chain (OKC) of throwing were considered, see (figure 1). The OKC model suggests that an overhand throw takes place similar to a whip unfurling with the proximal body sections moving first followed by the distal elements as seen in figure 1. This sequence of motion predicts the shoulder to rotate followed by the forearm with the hand moving last.

![Figure 1: Open Kinetic Chain (OKC) of the throwing motion, showing 6 positions from windup to follow through. The sequence of applied torques follow from (a) to (h) in this model, whereby the final rotational torque (h) should be about the wrist. The lower figures show the amount of trunk rotation during each sequence of the OKC throwing motion.](image)

METHODS

Subjects

More than 40 soldiers were asked to perform the same grenade throwing activities. Of these, 3 were chosen to wear the additional EMG and IMU sensors for kinematic data capture. Differences in height, weight and muscle mass were sought after when deciding the 3 participants to better represent the entire soldier population.
Apparatus
Four muscle groups known to be used during the overhand throwing motion were analyzed using the Noraxon myoMUSCLE EMG system at a sample rate of 3000Hz. Each of the 3 participants were right hand dominant and therefore the right external oblique, right lower trapezius, right infraspinatus, and left external oblique were studied. A 16 sensor wireless Noraxon myoMOTION IMU system, sampling at 200Hz, was worn by each participant to collect the 3D kinematic parameters of the throwing motion and the myoRESEARCH biomechanical analysis software was used to analyze them synchronously.

Set-up
Each of the two Noraxon systems used provide for wireless sensor communication and the ability to synchronize the data collection without additional equipment. The wireless EMG sensors were affixed to the skin of each subject using Noraxon double sided sensor tape and self adhering electrodes were used. Additionally, Noraxon neoprene body straps were provided to adorn the 16 wireless IMU sensors. The software used, myoRESEARCH 3.6, required only a portable laptop computer and allows for control of Noraxon hardware, data collection, analyses and processing. All of this equipment was operated outside on a training field using only the battery power of the laptop.

Procedure
While the formal 40+ person study was being conducted, 3 individual soldiers were selected and asked to wear the EMG and IMU sensors. One research assistant was able to adorn and calibrate the wireless sensors as each soldier waited for their respective turn to throw. Each of the 5 different grenades were thrown using 3 separate stations. Additionally, each throw was repeated to allow for a higher confidence in the collected data. Therefore each soldier threw a total of 30 grenades, 3 stations * 5 grenade styles * 2 throws. It was found that the high rotational velocities and linear accelerations experienced about the throwing arm resulted in the IMU sensors to saturate and therefore become unreliable after 2 consecutive throws. Calibration of the IMU sensors was therefore completed after each set of identical throws and was found to correct the problem. The EMG signals captured were processed using the myoRESEARCH 3.6 software by rectification and applying an 8th order Butterworth high pass filter with cutoff frequency of 0.1 Hz.

Overhand Throwing Biomechanics
To begin analysis we defined the phases of interest during the grenade throw as seen in figure 6. Both acceleration and position data was used to define both the phases and their transitions.

PHASES
1. Address
2. Arm Cocking
3. Arm Acceleration
4. Arm Deceleration
5. Follow Through
Address phase was defined as the moment showing no accelerations and before the throwing arm began to rotate.
The arm cocking phase began at the first sample showing shoulder rotations and ending when the arm began to accelerate in the forward direction.
Arm acceleration phase starts just after the shoulder reaches maximum external rotation and ends when the ball is released.
The first sample that measured a deceleration from the maximum, defined the beginning of the arm deceleration phase.
Once the throwing arm began to drop and cross the chest, the follow through phase began and ends once the rotational velocity about the throwing wrist measures zero.

Using these phases we calculated the total and average muscle activity, range of motion (ROM) of the shoulder, and accelerations about each the shoulder, elbow and wrist.

FIGURE 2: The above illustrates phases 2-5 of the overhand throwing motion used in the grenade throws. It is easy to see from this profile view the importance of shoulder range of motion during this motion.

Definition of analysis periods
When using multiple data collection systems it can be difficult to ensure proper sample time alignment and process the raw signals. The myoRESEARCH 3.6 software allowed for easy data viewing and manipulation as seen in figures 3-5 while giving robust signal processing options.

FIGURE 3: The above computer screenshot shows the 4 EMG signals and accompanyin 3D avatar data showing the six phases of overhand throwing; Address (1), Arm Cocking (2), Arm Acceleration (4-5), Arm Deceleration(6), Follow Through (7-8).
Each record had markers placed at 8 unique locations defining the 5 phases as seen in figure 3. From these markers the myoRESEARCH 3.6 software was able to give analytic results for EMG activities, arm accelerations and ROM reports as seen in figures 4-5.

![Image](image.png)

**FIGURE 4-5:** Above left shows an example report giving arm segment rotations including minimum/maximum angles achieved and total ROM. Above right is an example of the EMG report provided by myoResearch 3.6.

## RESULTS & DISCUSSION

### Study Aims

The aims of this study were:

1. To investigate the throwing experience, and the types of injuries associated with overhand throwing motions.
2. To characterize 5 grenades of different mass, specifically their respective impact on the human body.
3. To analyze at least a small percentage of possible biomechanical colorations present within the collected data.
4. To provide practical suggestions based on the findings from above.

### Open Kinetic Chain

It was determined that the Open Kinetic Chain model was most appropriate when discussing throwing grenades. The OKC was used to describe the pattern of the throwing motion 3-4. In the OKC pattern, body segments work like a linkage, with the distal end free to move and the proximal end fixed. The grenade throwing movement is an example of OKC motion, with the proximal segment accelerating the distal segment until the release. Flesig et al. 6 and Atwater 7 also indicated that the forces are accumulated for proximal to distal segments in the human throwing motion. Atwater 7 and Flesig et al. 8 also point out that in the human upper body throwing motion the force is transferred according to the kinetic chain principle, which proceeds from the proximal end to the distal end.
First, the trunk forward motion and leftward rotation are accelerated by respective joint torques produced by relatively large muscles located at the lower extremity and trunk. The shoulder horizontal flexion torque and internal rotation torque during this phase prevent the upper arm from lagging behind relative to the trunk. As a result, the angular velocity of the upper arm also increases with that of the trunk. Thus, the motions of the trunk and upper arm in the early phase are produced by the instantaneous direct effect from large proximal muscles. The angular velocities of the trunk and upper arm produced by the above mechanism are the sources of the velocity-dependent torque acting for the elbow extension. As a result, the elbow joint angular velocity increases, and concurrently, the forearm angular velocity relative to the ground also increases. The forearm angular velocity subsequently accelerates the elbow extension.

**FIGURE 6:** The Open Kinetic Sequence between the shoulder (yellow), elbow (red) and wrist (green) showing the most proximal segment moving first followed by the second and lastly the most distal body segment.

**Grenade Comparison**

<table>
<thead>
<tr>
<th>General Details</th>
<th>Grenade 1</th>
<th>Grenade 2</th>
<th>Grenade 3</th>
<th>Grenade 4</th>
<th>Grenade 5</th>
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<tr>
<td>Mass</td>
<td>16 oz</td>
<td>18 oz</td>
<td>22 oz</td>
<td>24 oz</td>
<td>18 oz</td>
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<td>Round</td>
<td>Round</td>
<td>Round</td>
<td>Ellipsoid</td>
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<td>EMG Analysis (mV)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Right External Oblique (Max/Mean)</td>
<td>249/497</td>
<td>314/668</td>
<td>381/562</td>
<td>456/689</td>
<td>417/702</td>
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<td>Right Lower Trapezius (Max/Mean)</td>
<td>416/669</td>
<td>373/611</td>
<td>144/287</td>
<td>192/291</td>
<td>293/558</td>
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<tr>
<td>Right Infraspinatus (Max/Mean)</td>
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<td>218/273</td>
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<tr>
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<td>382/1059</td>
<td>1034/1842</td>
<td>944/1143</td>
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<td>Backward trunk tilt angle</td>
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<td>8.6</td>
<td>8.7</td>
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<td>Wrist flex angle (max)</td>
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<td>Wrist extend angle (max)</td>
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<td>69.2</td>
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<td>32.8</td>
<td>33.9</td>
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<td>27.4</td>
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<tr>
<td>Kinetic energy percent of wrist</td>
<td>8.1</td>
<td>9.8</td>
<td>7.2</td>
<td>14.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

**FIGURE 7:** The above chart shows the EMG and 3D IMU Motion analysis of the total throwing motion, including all 5 predefined phases of the distance throw. Note the EMG activity increases with increased mass while the external shoulder rotation decreases with increasing mass. The OKC model predicts the kinetic energy percentage should be largest for shoulder and smallest for wrist, which corresponds with experimental findings.
**FIGURE 8:** The chart above shows the data for only the accuracy throws of this study. Clear differences appear when compared to the distance throw including a higher average EMG activity over a longer period of time and measurably smaller ranges of motion for the throwing arm.

**System Errors**

The EMG data from 4 of the 90 total grenade throws could not be properly analyzed as the gear worn by the participants pulled on the lead wires resulting in a poor signal. This problem was recognized by the research assistant and the EMG sensors were repositioned with good resultant signal quality.

The rotational velocities measured about the arm during an overhand throw has been demonstrated as the single fastest motion capable by the human body (6-7). During this study participants exceeded 5000 degrees per second about the shoulder, elbow and wrist which resulted in the myoMOTION IMU sensors to saturate. After the follow through phase the avatar displayed some discontinuity visibly with the participants. This was mitigated by recalibrating the myoMOTION system between each pair of like throws. The data analyzed for this study was not affected by the IMU data saturating during the Arm Deceleration phase as all external shoulder rotation occurs before this time.

Video was collected during the study but was not considered during analysis due to privacy concerns. The addition of this video data would allow for a second method to measure both velocities and angle changes giving a higher level of total confidence to the report.
CONCLUSIONS

As grenade throwing remains an important training requirement for soldiers, this study intended to examine the physical stresses on the body. Injuries related to the overhand throwing motion have been investigated and found to have a high correlation to reduced external shoulder rotation and torque about all joints of the throwing arm. The overhand throwing motion produces some of the fastest movements capable by humans. In this study, for example, each participant exceeded 5000 degrees per second of rotational velocity about both the elbow and wrist while accelerating at over 16G's.

Applying the OKC to our 16 segment rigid body model allowed for work and energy to be estimated for each throw measured. This method shows that an increase in grenade mass over the range tested requires more work and produced higher torques about the throwing arm. Collection of muscle activity from dominant muscle groups also supported this finding.

The AFG, prolate spheroid shaped grenade, was found to be a different throwing motion than that characterized for the round style. As these two movements have unique torque requirements the measured muscle activity could not be directly compared for this study. Analyzing only the round grenade shows an increase in duration and maximum amplitude for increased object mass.

From these two findings it is recommended that the 16 ounce grenade be used to reduce chance of injury and fatigue. Beyond its relevance to understanding injury, rotational range of motion at the shoulder may also have significant performance consequences. It is therefore recommended that further investigation take place to determine the impact of grenade mass on the soldier's throwing proficiency over time.
REFERENCES


APPENDIX A (additional figures)

FIGURE 8: Accelerations experienced on the dominant throwing upper arm, in all three axis. Markers again indicate the phases of throwing considered within this report.

FIGURE 9: The EMG of all 4 muscle groups measured after the signals have been rectified and filtered.
APPENDIX B (sample of participant B’s EMG analysis)

Noraxon Standard EMG Analysis

FIGURE 10: The EMG of throwing 4 different grenades for accuracy. The similarities in waveforms between measurements gives a good indication of well working equipment and much more to learn from this already collected data set.
FIGURE 10: The EMG of throwing 4 different grenades for maximum distance. Before using more advanced analysis techniques, it is possible to see the correlation of increased mass to increased muscle activity.