EVALUATING REHABILITATION THROWING PROGRAMS & INJURY DATASETS WITH ACUTE:CHRONIC RATIOS AND PHYSIOLOGY-BASED FATIGUE UNITS

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INTRODUCTION:

The advancement of player tracking technology has allowed for the development of progressive athlete biomechanical models. Notably, the increased accessibility and usability of tracking technology has allowed for biomechanical data to be collected more frequently. This growth in usability has opened new paradigms of joint and muscle-specific workload algorithms to be applied to elite athletes.

As these platforms have matured, the insights gained from historical data and meticulously recorded injury incidents have begun to shed light on quantifiable causes of injury. This paper aims to explore state-of-the-art joint and muscle-specific workload algorithms as they relate to concepts of fatigue, injury, and rehabilitation of a thrower’s arm. Furthermore, this paper will compare various case studies of real injury-tagged datasets to current standards in thrower’s rehabilitation, including protocols from the Andrews Institute (AI), Texas Medical Institute (TMI), and Mayo Clinic (MAYO).

Moreover, this paper proposes an optimized return-to-throwing program to advance the standard of care. The optimized system utilizes novel peak-torque estimations using partial effort data from the motusTHROW sleeve, appropriate chronic workload progression, minimized fluctuations in the acute:chronic workload ratio, and minimized muscle fatigue units.

WORKLOAD AND MUSCULAR FATIGUE

Fatigue is the single most significant predictor of pitcher injury. It has been linked to a 36x increase in injury likelihood.³ The concept is simple, but the physiological background is staggeringly complex. In order to apply appropriate workload algorithms and make effective decisions from workload data, fatigue must first be understood from a “bottom-up” approach.

Fatigue will be referred to with concepts of central and peripheral muscle fatigue of muscle groups that protect the ulnar collateral ligament (UCL)—the pronator group. Seen in Figure 1, these pronator muscles (flexor digitorum superficialis, flexor carpi radialis, pronator teres), when activated, produce a varus torque about the elbow joint. To prevent strain or lengthening of the UCL, the valgus torque produced by a pitch must be counteracted by the varus torque produced by the muscles. When these muscles become fatigued, more valgus torque is placed on the UCL instead of supported by the muscles,

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Figure 1. Pronator muscle (flexor digitorum superficialis)
leading to microtrauma of the ligament. These microtrauma accumulate and result in a final full-thickness tear. How do these pronator muscles become fatigued?

Fatigue has been defined as “the exercise-induced reduction in the ability of the muscle to produce force or power, whether or not the task can be sustained”. One source of muscle fatigue lies in the ability for an action potential to travel from the central nervous system (CNS) to the muscle fiber. Proper CNS readiness ensures that muscles can contract with their maximal potential. In fact, Cadore et al\(^2\) reported a 22.2-27.3% increase in muscle conduction velocities (MCV) after a 6-week strength program. This supports a notion that as fitness increases, so do the efficiency of neuromuscular junctions, which is extremely important in a muscle’s ability to generate force.

Another important factor related to muscle force potential is a simple one—muscle size measured in cross-sectional area. Typical strength programs usually refer to a “hypertrophy” period, in which muscle fibers increase in size and new fibers are grown. Young et al\(^3\) showed a 20% increase in muscle thickness over a 7.5-week training regimen.

As both neuromuscular junctions and muscle volume increase with fitness, so does the efficiency of biochemical energy systems. The primary biochemical system with fast-twitch muscle fibers is the conversion of glycogen to ATP, which produces final muscle fiber contraction and force output.

The most obvious factor that inhibits fiber contraction is the absence of glycogen and the ability to create ATP. A bout of maximal effort activity that depletes glycogen stores in fast twitch fibers, may take up to 60 seconds to replenish. If glycogen is not readily available in the cell or bloodstream, the body can produce more through gluconeogenesis (metabolism of proteins).

A more complex factor that inhibits force generation, is the state of hydration and ionic mineral concentration in a muscle cell. In dehydrated states, muscle fibers have higher levels of friction and lower outputs of force. As well, loss of critical minerals such as calcium, sodium, and potassium have significant effects on the CNS’ ability to deliver action potentials to a muscle cell. Both of these situations occur after intense bouts of activity, and often lead to delayed onset muscle soreness (DOMS).

Modeling aspects of muscular fitness and fatigue began with Dr. Tim Gabbett, coining the term acute:chronic workload ratio (ACWR). To compute this workload measures with motusTHROW data the workload of each throw must be computed. This is done by normalizing valgus torque by height and body mass of the player and by then exponentially weighting the normalized value (equation 1). The exponential weight of 1.3 was chosen based on NASA’s “Daily Load Stimulus” research regarding bone loading. The exponential weight requires further validation.\(^7\)

\[
WL_{throw} = \left(\frac{\text{valgus}}{\text{nt+wt}}\right)^{1.3}
\]  

(1)

Next, daily workloads are computed as the total sum of workload of each throw (equation 2). Following this, acute and chronic workloads are computed as a rolling averages of daily load. Typically, acute
workloads are seven(7) day averages and chronic workloads are twenty-eight (28) day averages. To combat problems with using these fixed divisors early in throwing activity (first 14 days), dynamic divisors are used (equation 3-4). Finally, each day the ACR is computed as the acute workload divided by the chronic workload (equation 5).

\[
WL_{Day} = \frac{\sum_{\text{throw}=1}^{n} WL_{throw}}{1} \\
WL_{Acute} = \frac{\sum_{\text{Acute Divisor}=1}^{7} WL_{day}, \text{Acute Divisor} = 3 - 7}{1} \\
WL_{Chronic} = \frac{\sum_{\text{day}=1}^{28} WL_{day}, \text{Chronic Divisor} = 5 - 28}{1} \\
ACR = \frac{WL_{acute}}{WL_{chronic}}
\]

For example, on day one, the acute divisor is 3, and on day two, the divisor increments to 4. Further, on day seven, the divisor reaches its maximum of 7. Conversely, the chronic divisor in this example starts at 5 and increments each day, such that on day seven, it’s value is 11. The chronic divisor continues to increment dynamically until it reaches a maximum of 28.

The resulting workload data from ACWR calculations can be seen below in Figure 3. In this sample dataset of a motusTHROW user, the user was exposed to two elevated ACWR periods during his return-to-throwing program. Mehta et al\textsuperscript{4} reported a 25-fold increase in injury risk when throwing with an ACWR of 1.3 or greater. This specific pitcher repeatedly threw with ACWR greater than 2.0, likely placing the athlete at high levels of fatigue. Furthermore, the athlete was exposed to high ACWR during periods of low chronic workload.

![Figure 3. Case study of motusTHROW data preceding a UCL Tear](image)

Chronic workload is extremely relevant to muscle physiology and our efforts at modeling fatigue. When chronic workload is low, a muscle may likely have fewer neuromuscular junctions. Furthermore, ionic balance (hydrogen ion accumulation, dehydration, Na/Ca+ ion concentration) of an untrained muscle is poor after high effort workouts. As chronic workload builds, fitness ensues, and the muscles are able to reach ionic balance faster and “recover”. This allows the use of Chronic Workload units as direct variables in the models of muscular fatigue.
MODIFIED FATIGUE UNITS

Acute and Chronic workloads provide extremely actionable data points in regard to identifying aspects of fatigue. While ACWR provides a strong measure of acute (weekly) fatigue and chronic workload provides a strong measure of fitness, additional physiological aspects of fatigue exist. Therefore, two additional models of fatigue were explored. The first model, adapted from Sonne et al\textsuperscript{5}, explores fatigue within a single day—ATP Fatigue Units. The second model explores recovery rates of delayed-onset-muscle soreness (DOMS) over the scale of days and weeks—ION Fatigue Units. Combined with ACWR and Chronic Workload, these cumulative measures of fatigue may help advance the field of workload monitoring.

At the muscle level, ION Fatigue Units model the ionic balance of the muscle (hydrogen ion accumulation, dehydration, Na/Ca+ ion concentration, etc.). This model is adapted from concepts of Di Newham et al\textsuperscript{8}, who tested recovery rates of maximum isometric strength following repeated high-force eccentric exercises, over 7 weeks. The work noted that after the first bout of maximal effort training, it took the eight subjects (on average) almost 3 weeks to regain maximum muscle-voluntary-contraction (MVC) strength. After the next training session (week 3), it took the subjects about 1 week to recover maximum MVC strength. After the final training session (week 6), it took the subjects about 4 days to recover maximum MVC strength.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Maximal isometric strength during training period. Exercise was performed in 1st, 3rd, and 8th wk. MVC, maximum voluntary contraction.}
\end{figure}

To capture this physiological effect, ION Fatigue Units were devised. The concept begins with defining a one-day-workload in equation (2). This exponentially-weighted valgus load represents a summation of volume and intensity of the throwing forearm muscles. The ION Fatigue Units, on the day of training are equal to this one-day-workload, plus the sum of previously decayed workload. Each subsequent day, the training-day’s workload in the ION Fatigue Units decay at a variable rate (depending on the Chronic
workload status). When the Chronic workload is low, the one-day-workload decays over an eight (8) day period. As the Chronic workload builds, the decay rate quickens to as short as three (3) days.

Mathematically, ION Fatigue Units were modeled to decay over a variable period of days (3-8 days). The decay rate ($\lambda$) is linked to the Chronic workload level and shown in equation (6) and Figure 5. The exponential decay is modeled with a gaussian decay.

$$Fatigue_{ION}(t) = \sum_{t=0}^{T} WL_{day} \frac{1}{\lambda_{ION}\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t-t_0}{\lambda_{ION}})^2}$$ (6)

At the motor-neuron level, ATP Fatigue Units model the accumulated ATP consumption of a muscle. This model is adapted from Sonne et al., who has applied an extensive three-compartment model of fatigue to baseball pitcher’s using pitchFX data. The concept begins with each throw representing a near-maximal muscle contraction (isometric, concentric, or eccentric). With each near-maximal contraction, the muscle demands conversion of glycogen to ATP for the motor neuron to generate force. Rapid contractions initiate a “debt” of energy, and thus a lack of ability to generate maximal force. With ample rest, the muscle regains glycogen stores and ATP use is restored.

Figure 5. ION Fatigue Units Decay Rates for various Chronic Workload Units (modeled by Motus).

Sonne’s model was adapted to use each throw’s magnitude of valgus torque as inputs to the ATP Fatigue Unit model. After the first throw, the ATP Fatigue is calculated as the workload of a throw.
(equation 1). The ATP Fatigue Units then decay at a variable rate of 60-240 seconds. As the next throw is made, the ATP Fatigue Units compound as a sum of the current ATP Fatigue Unit plus the workload of the next throw. Furthermore, the variable decay rate was chosen to add a complexity that captures the arm’s ION Fatigue Units. When the ION Fatigue Units are low, the ATP Fatigue Units decay faster (60 seconds). When the ION Fatigue Units accumulate higher, the ATP Fatigue Units decay slower (up to 240 seconds).

Mathematically, ATP Fatigue Units were modeled to decay over a variable period of 60-240 seconds (depending on the ionic balance of the muscle). The decay rate of ATP fatigue is heavily influenced by the ION Fatigue Units, and is seen in equation (7).

\[ Fatigue_{ATP}(t) = \sum_{t=0}^{\text{workload}} W_{Day} \frac{1}{\lambda_{ATP}\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t}{\lambda_{ATP}})^{2}} \]  

(7)

**APPLYING WORKLOADS, ATP, AND ION FATIGUE UNITS TO INJURY DATASETS**

To provide context to these workload and fatigue concepts, six types of injuries were extracted from the Motus database: rotator cuff strain, shoulder impingement, middle trapezius stain, UCL Grade I sprain, UCL Grade II sprain, and full UCL tear.

**Rotator Cuff Strain:**

Seen here is data from a user who sustained a rotator cuff strain. This pitcher progressed from 0-10 chronic workload units in a mere 27 days. In the week prior to the injury, the ACWR was elevated above 1.3; however, ION Fatigue Units were elevated over 50% of the pitcher’s return regimen. Furthermore, the day of the injury, ATP Fatigue units were the highest. This pitcher was subjected to a variety of fatigue and was likely injured due to throwing too frequently within the last day of this analysis. ATP was likely depleted from the shoulder muscles, leading to excess force on the shoulder joint capsule.

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![Figure 7](image-url) **Figure 7.** ATP Fatigue Units Decay Rates for various ION Fatigue Units (modeled by Motus).
Shoulder Impingement:

Data preceding a shoulder impingement was extracted from another pitcher in the Motus database. Here, there is a clear example of a high ACWR on day 31 (4 days prior to the injury being reported). During the last 5 days of throwing, the pitcher experienced highly elevated ACWR (over 2.0).

Furthermore, on Day 31/35, the pitcher experienced the highest ATP and ION Fatigue Units. The pitcher threw over 20 consecutive minutes without rest, resulting in a large ATP Fatigue Unit spike. The accumulated workload was very high on this day (perhaps reflecting load exceeding capacity to tolerate load). It is likely that the pitcher injured himself on Day 31/35 and attempted to throw through pain and the injury on Day 35/35.

Middle Trapezius Strain:

Data preceding a middle-trapezius strain was extracted from the Motus database. On the day of injury (day 13), the ACWR was highly elevated (over 2.0). When inspecting physiological fatigue measures, the data does not show any large ATP Fatigue accumulations. The pitcher’s workloads within each day had plentiful rest throughout the day; however, the ION Fatigue units were elevated (above 40) for the last 4 days of throwing.

Coupled with a low chronic workload, the pitcher likely increased daily workloads too quickly, resulting in ionic imbalance in the muscle and ultimately a highly fatigued state.
**UCL Grade I Sprain:**

Data preceding a Grade I UCL sprain was extracted from the Motus database. On the day of the injury, the ACWR was moderately elevated (over 1.5). In the week preceding the event, the pitcher’s ACWR was continually elevated.

Furthermore, the ION Fatigue Units were highly elevated (over 6) for the last week of rehab—indicating too little rest between throwing days and too much intensity on the day overall.

ATP Fatigue Units were also elevated in the last week of throwing, indicating too little rest between throwing sets within the day.

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**UCL Grade II Sprain:**

Data preceding a Grade II UCL sprain was extracted from the Motus database. On the day of the injury, ACWR were 0.0, due to the pitcher resting for a week prior to throwing. It is suspected that the injury occurred a week prior to this, when workloads and fatigues were elevated. However, there is evidence that having troughs in ACWR also has an association with injury risk.

One week prior to the event, ACWR was slightly elevated (over 1.3). Furthermore, ION Fatigue Units were elevated (over 40) for two days during the 20-day throwing program.

It is important to note that on day 4, a high one-day workload of 30 was done by the pitcher, with a chronic workload of <2.0. Loading the arm with this much workload requires intense throws with high valgus torque. Placing this much torque early on in a return-to-throw program is not recommended.
**UCL Tear:**

Data preceding a full UCL tear was extracted from the Motus database. On the day of the injury report (Day 64), the ACWR was low (<1.0), the ION Fatigue Units were low, and the ATP Fatigue Units were low. This pitcher likely sustained a Grade II sprain prior to this event.

In the 64-day return-to-throwing program, the pitcher was exposed to two highly elevated ACWR periods (over 2.0). The first period occurred on day 15, when the pitcher’s one-day workloads spiked by a factor of 4. This large spike in acute load, coupled with a low chronic load represents an elevated ACWR.

The second period of highly elevated ACWR occurred on day 40, when the pitcher increased throwing frequency from 3x per week to 6x per week. Coupled with increased one-day loads, this increase in daily throwing frequency led to a large acute spike relative to the chronic workload.

### COMPARING WORKLOADS AND FATIGUE UNITS ACROSS LEADING REHAB THROWING PROGRAMS

Given the examples of elevated fatigue and workload as it relates to thrower injury, it appears that most throwing injuries occur early in a return-to-throwing program. Contextually, this is extremely compelling. Consider a pitcher who picks up a baseball for the first time in January (chronic load = 0). This pitcher needs to be game-ready by April 1st and embarks upon a throwing program to build up arm fitness. In order to build up chronic workload, weekly loads need to exceed that of the previous week. After a proper progression, the pitcher reaches April with forearm muscles that have neuromuscular junctions with fast MCV, muscle volume, and stamina. It is common, however, that this pitcher never makes it to April.

The reason we see so many injuries in spring training is because frequently, pitchers add too much workload within a day or within subsequent weeks and become subjected to excess fatigue. Therefore, this next portion of the analysis simulates four leading return-to-throwing programs to demonstrate the fatigue our athletes are subjected to during our standard. The programs analyzed include: The Andrews Institute, Texas Medical Institute (TMI), Mayo Clinic, and Ohio State University Sports Medicine (OSU).
Andrews Institute Rehabilitation Protocol

The Andrews protocol is the most cited return-to-throwing program in recent literature. It has been adapted by leading physical therapists and has existed for decades. The general approach progresses a pitcher through increments of 25x throws each week with 2-3 sets (with rest in between sets), while increasing long-toss distance from 45 ft to 180 ft over seven weeks. Phase 2 of the Andrews program consists of progressive mound work over nine weeks, while increasing intensity from 50% to 100% effort. Notably, the program introduces breaking balls late in the mound work phase.

To simulate workloads for the Andrews program (and others to follow), effort was estimated using the distance prescription for each step in the return-to-throwing program. For instance, 45 ft represented 25% effort (45 ft/180 ft) and 180 ft represented 100% effort (180 ft/180 ft). Throws were modeled using the Motus database average time-between-throws of 14 s, and where applicable, prescribed rest periods were added between sets. Warm-up throwing was modeled with a linear increase in effort up to the prescribed limit. Where applicable, prescribed warm up times were converted to throw counts using the time-between-throws average of 14 s. Finally, workloads and Fatigue Units were calculated after each throw from each day in the program were simulated.
Data from the Andrews Rehab simulation show a few concerning points. While the program is an easy-to-follow regimen, it exposes pitchers to high ACWR over the first 36 days of return-to-throw. Simply, the first phase of the rehabilitation is too aggressive in terms of ACWR. Furthermore, the later stages of Phase 1 expose the pitchers to the highest ION Fatigue units given the rapid development of throwing distance.

The program also exposes pitchers to elevated ACWR midway through Phase 2, when effort prescriptions are higher. High elevated ACWR alongside high elbow valgus torque are likely a poor combination for arm health. On day 70 of the rehabilitation program, pitchers are also exposed to high ATP Fatigue Units, due to too little rest within the day’s prescription.

Additionally, the program does not prescribe effort during the long-toss phase (Phase 1). Since pitchers can throw at high or low intensity at either 90 ft or 120 ft or 150 ft, distance should not be the only variable in the equation of prescribing a return-to-throw program.

**Texas Medical Institute Rehabilitation Protocol**

The TMI protocol approaches rehabilitation from a different perspective than the Andrews protocol. The TMI protocol begins by prescribing 25 throws per day, 3 days per week, every other day. It progresses by increasing to 2x25 throws per day, to 3x25 throws per day on a weekly basis. Once the 3x25 throws per day is reached, the athlete is then progressed to a further throwing distance; however, the volume is rest back to 25 throws per day. The volume progression repeats, alongside distance, until a maximum throwing distance of 120 ft is reached. Notably the TMI program requires rest between sets and introduces breaking balls late in the mound-work phase near the end of the program.
The TMI protocol is unique and creative in many ways. Amongst the notable workload actions, the TMI protocol begins to blend throwing frequency from 3x per week to 4x per week, all the way through 7x per week near the end of the throwing program. The program is also almost twice as long (30 weeks) as the Andrews protocol (16 weeks), allowing for more conservative chronic workload progression. The TMI program also is the only program to prescribe an entire week of rest.

However, the TMI program has a few concerning aspects. Early in rehabilitation, the program exposes pitchers to moderately high ACWR’s (over 1.6). The cyclical nature of regressing throwing volume seems to produce slightly variable ACWR’s over the duration of the rehabilitation. Further, the progression from throwing 3 to 5 days per week does not adequately regress the athlete’s throwing volume to allow for minimized ACWR spikes.

**Mayo Clinic Rehabilitation Protocol**

The Mayo Clinic rehabilitation protocol seems to blend aspects of the TMI and Andrews protocols in a methodical manner. At a length of 24 weeks, it’s more conservative than Andrews protocol and more aggressive than the TMI protocol. The program begins with extremely light effort throwing (usually throwing with a tennis ball) and requires throwing 3 days per week while resting every other day. Similar to both the Andrews and TMI programs, the Mayo clinic program progresses a pitcher’s effort by prescribing further throwing distances each week. Notably, the program also includes warm-up throws and rest periods between sets, while progressing to breaking balls late in the mound-work phase of rehabilitation program.
The Mayo clinic protocol has its concerns. Early in the program, the protocol exposes athletes to highly elevated ACWR (over 1.9) and moderately elevated ACWR (over 1.5) for the first 45 days. The only caveat to this concern is that the elbow valgus torques in these early stages are so low, that they will likely not strain the ligament in a fatigued state. However, as effort progresses near day 90, ACWR is elevated again (over 1.5).
TOWARDS AN OPTIMAL REHABILITATION THROWING PROGRAM

After analyzing the leading rehabilitation programs using Motus’ workload and fatigue algorithms, an optimal rehab throwing program philosophy and guideline was created.

1. Rehabilitation programs should prescribe effort within each day (not just distance).
2. Rehabilitation programs should include ample rest between throwing sets (if applicable).
3. Rehabilitation programs should build chronic workload in a safe fashion.
4. Rehabilitation programs should linearly increase peak elbow torque exposure.
5. Rehabilitation programs should periodize throwing frequency within a week (not monotonous volumes each day).
6. Rehabilitation programs should increase throwing-days-per-week frequency from every-other-day to multiple days in a row.
7. Rehabilitation programs should limit exposure to elevated ACWR, ION Fatigue Units, and ATP Fatigue units.
8. Rehabilitation programs should consider factors that moderate the workload-injury relationship (e.g. age, injury history, strength), along with factors that influence training adaptations (e.g. biomechanical factors, sleep, psycho-emotional stress, etc.).

In order to remove throwing distance from the equation of prescribing effort to a pitcher, a Motus sleeve needs to be used to capture a torque-velocity profile of an athlete. Since most athletes do not wear the Motus sleeve before an injury, game-torque levels will not be known; however, game-ball velocity levels will be known. As an example, a current pitcher, and motusTHROW user, undergoing rehabilitation underwent a calibration process as follows:

- **a)** Captured elbow valgus torque and ball velocity at 50% effort.
- **b)** Captured elbow valgus torque and ball velocity at 75% effort.
- **c)** Created linear regression of data to extrapolate to peak torque levels.
- **d)** Used extrapolated peak torque to periodize effort in a rehabilitation program alongside ACWR.

![Figure 8. Torque Extrapolation and Loading profile during Motus’ optimized Rehabilitation](image-url)
In coordination with the Torque Loading profile, an optimized rehabilitation program was devised to maximize adherence to the philosophy laid out above. Primarily, the Motus rehabilitation program ensures that ACWR are minimized below elevated levels throughout the program. Additionally, the program progresses an athlete to reach a high chronic workload (over 10.0).

Notably, the program progresses throwing frequency per week from every other day, to 2 consecutive days, to 3 consecutive days, to 4 consecutive days. Motus was not able to optimize the program to allow for daily throwing in a period of 24 weeks.

Furthermore, the Motus program mimics the Mayo Clinic, TMI, and Andrews programs by prescribing increasing sets of throwing repetitions with prescribed rest intervals between sets.

It should be noted that the Motus program does expose athletes to slightly elevated ACWR’s early in the program; however, since elbow torque levels are dramatically reduced (and controlled), risk is minimized if a fatigue state ensues.

![Figure 9. Optimized Motus Rehabilitation Program](image-url)
REFERENCES


REHABILITATION PROGRAM LINKS