Rapid muscle activation changes across a competitive collegiate female soccer season

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Abstract

Objective: The purpose of this study was to examine the effects of a competitive soccer season on rapid activation properties of the knee extensors and flexors in Division II female soccer players. Methods: Eighteen collegiate female soccer players participated in the present study, however, due to injuries during the season a final sample of 16 players were included for study analysis. Participants performed two maximal voluntary isometric contractions (MVICs) of the knee extensors and flexors before, during, and at the end of a competitive college soccer season. Electromyography root mean square (EMG RMS; µV), rate of EMG rise (RER; %Peak EMG•s−1), and electromechanical delay (EMD; ms) were examined on both legs for the knee extensors and flexors. Results: EMG RMS at early time intervals (0-50, 0-100, and 50-100 ms) and RER at 0-75 ms for the knee extensors and flexors significantly increased from the pre-season to the end of the season (P≤0.010-0.026, η2=0.36-0.81). EMD of the knee flexors significantly decreased at the mid-season and the end of the season compared to the pre-season (P<0.001, η2=0.95). Conclusions: These findings may have important implications for monitoring improvements on thigh neuromuscular activation and developing lower extremity injury prevention strategies during a competitive collegiate female soccer season.

Keywords: Female Athletes, Motor Control, Neuromuscular Adaptation

Introduction

A variety of athletic and physically active populations perform plyometric exercises and muscle speed-strength training to facilitate explosive muscle strength development1-2. It is well recognized that explosive strength characteristics such as rate of torque or force development (RTD or RFD) are good indicators of whole muscle contractile speed, which is influenced by motor unit activation2-5, muscle fiber type6-7, and sensitivity of myofilaments to Ca2+8. It is suggested that individuals with greater motor unit activation and/or firing rates [i.e. a rate of EMG rise (RER)] can generate greater and more rapid muscle force production (i.e. RTD or RFD) responses during important functionally-related tasks such as running, accelerating, and cutting2-5. In support of this notion, increases in RER and RFD have been reported following an intervention of heavy-resistance strength training5,9,10. This finding indicates that heavy resistance training induces improvements in RFD that are accompanied by improvements in rapid muscle activation (RER) which may be due to an increase in motoneuron firing frequency5.

While resistance training can improve rapid force production capacities, it has been suggested that this type of training can also elicit a decrease in the electromechanical delay (EMD)11. The EMD is the time interval between the onset of electrical activation and the onset of muscle force or torque production. EMD is directly correlated with the stiffness of the series elastic component (SEC) and excitation-contracting...
coupling of the myofilaments. Previous research has suggested that a stiffer SEC will result in lower EMD values. Although a majority of previous literature has assessed the acute effects of stretching or fatigue interventions on EMD, a previous study reported that chronic training using plyometric exercises caused a decrease in the EMD because of an increase in stiffness of the SEC. Additionally, it has been reported that a long-term plyometric and heavy-resistance strength training program would improve neural drive in the central and/or peripheral nervous system, which could enhance force or torque production during a rapid voluntary contraction and reduce the risk of injury.

EMD is directly related to mechanical and neural properties, and has commonly been assessed either at baseline levels, or at specific time points during training to monitor neuromuscular performance changes in recreationally active individuals. Each team-based sport, and respective position requires different in-game movements and performance demands. To perform such tasks successfully, coaches and training staff have been heavily focused on developing sport-specific plyometric and high-intensity intermittent strength training programs for their athletes in hopes to improve a number of neuromuscular characteristics including firing frequency of motor units, synchronization, and muscle activation, which would lead to improved rapid force production capacities of the muscles and help achieve the ultimate aim of improved sport performance.

Although previous literature suggests that neuromuscular properties can be affected based upon the mode of exercise (i.e. resistance training, plyometrics or high-intensity intermittent training) performed during a season in a variety of different sports, there is still limited research on the neuromuscular activation changes that occur across an entire competitive season for collegiate women's soccer players. Documenting these neuromuscular properties across a season would help elucidate the physiological effects at the neuromuscular level and help provide mechanistic insight regarding training and/or competitive sport participation adaptations. Moreover, previous studies have shown significant differences in maximal and rapid strength between the knee extensors and flexors. Previous research has also established strength differences between the dominant and non-dominant leg. Because these differences in muscle strength may be due to differences in neural activation characteristics, it may be of great value to analyze the neural properties of both muscles and limbs to determine if such factors play a role in the neural changes that occur across a competitive soccer season. Therefore, the purpose of the current study was to assess muscle activation characteristics including electromyography (EMG), rate of EMG rise (RER), and EMD for the knee flexors and extensors of both legs in collegiate women's soccer players at preseason, midseason, and after the end of a competitive soccer season. We hypothesized that the muscle activation characteristics for the knee flexors and extensors improves from pre-season to the end of the season due to the physical demands of the soccer players' in-season strength training and sport-specific activity.

Table 1. The standardized team training and practice routine.

| Days/week | Exercise                      |
|-----------|-------------------------------|
| Pre-season (May-August) | Days/week | Exercise                      |
| 2-3       | Weight training               |
| 2-3       | Cardio exercises              |
| 1-2       | Plyometric exercises          |
| In-season (August – November) | Days/week | Exercise                      |
| 1-2       | Weight training               |
| 1-2       | Mobility and coordination training |
| 0-1       | Aquatic exercise              |
| 3-4       | Team practice                 |
| 2         | Soccer Game (Friday and Sunday) |

Methods

Participants

Eighteen female collegiate soccer players (age=20.21±1.01 years, height=167.24±5.36 cm, mass=64.87±7.31 kg) volunteered to participate in the present study. The study was approved by the institutional research board and all subjects signed an informed consent document prior to study participation. All participants completed a health history questionnaire to determine study eligibility. Inclusion criteria consisted of participants who had not experienced any lower-extremity injuries, head trauma (including concussion), or other medical conditions that potentially influences their neuromuscular function within six months prior to the first data collection in August (preseason). During the athletic season, we had two participants who experienced non-contact Grade 3 knee ligamentous injuries. Those participants were removed from the follow-up assessments and analysis. No other participants experienced any lower-body injuries. Therefore, the present study is only reporting on the participants (n=16) who remained healthy and completed all assessment sessions throughout the season. Using G*Power software (version 3.1.9.2; Heinrich Heine University, Düsseldorf, Germany) and assuming a moderate effect size, it was determined that a minimum of 16 participants were needed to achieve adequate statistical power (0.80) at an alpha level of 0.05.

All participants performed the team workouts and training programs through the pre- and in-season that were designed and implemented by the team's strength and conditioning coaching staffs. During the pre- and in-season, each player performed the standardized team training routine (Table 1), which included a weight training program targeting the lower extremities using weightlifting exercises such as the back squat and leg press. The team's strength and conditioning coaches adjusted the volume and intensity of the workout sessions which involved subjects performing 4 sets of 8-10 repetitions at 70-80% of 1RM, every other week. During the season, the intensity was adjusted for each exercise.
based on the estimated 1RM. The estimated 1RM was
determined using a previously described procedure20 and
was measured immediately before the season (preseason)
and reassessed each month during the season. In addition
to specific strength and conditioning workouts, the team
played their regular season soccer games each week on
Friday and Sunday, while Monday was typically a day-off. The
team also practiced on Tuesday, Wednesday, and Thursday
of each week for an hour and half to two hours each day.
Each practice consisted of soccer-specific activities including
position drills and game-like training using a half- and/or full-
soccer-field. Furthermore, the team’s soccer coaches closely
monitored each subject’s practice and play time and strength
and conditioning workouts to ensure subjects were not being
over-trained. All participants adhered to the aforementioned
schedule (i.e., training workouts, practices, and games).

Procedures

To avoid the effects of neuromuscular fatigue on muscle
activation characteristics, each participant was instructed to
refrain from any vigorous physical activity or exercise 24
hours prior to each testing session. Participants reported to
the laboratory on four separate occasions which included:
1) familiarization (48 hours prior to the baseline assessment),
2) baseline measurement (pre-season, prior to the start of the
regular season; mid-August), 3) 1st follow-up (mid-season, 4
weeks after the baseline measurement; mid-September), and
4) 2nd follow-up (end of season, 8 weeks after the baseline
measurement; mid-October).

During the familiarization session, participants completed
the informed consent form and health history questionnaire
to ensure their eligibility for the research study. Their
demographic information was then collected (i.e., age, height,
weight, and dominant leg). The dominant leg was determined
as the leg the participants preferred to use when kicking a
soccer ball. After collecting demographic information, all
participants were familiarized with the testing procedures
by performing several submaximal to maximal voluntary
isometric contraction (MVIC) trials of the knee extensors and
flexors on both legs, with 1 minute of recovery
between each MVIC and 3 minutes of recovery between legs
and muscle groups. Participants were verbally instructed to
“push” or “pull” “as hard and fast as possible” for a total of 3
to 4 seconds during each MVIC. The order of the dominant
and non-dominant legs and knee extension and flexion MVICs
was randomized for each visit and participant.

Surface Electromyography Recording

Surface electromyography (EMG) was recorded during
each MVIC for the knee extensors and flexors using bipolar
pre-gelled Ag-AgCl self-adhesive disk electrodes (EL-502;
Biopac Systems, Inc., Santa Barbara, CA) with a center-to-
center interelectrode distance of 20 mm. The electrodes
were placed on the rectus femoris muscle for the knee
extensors at 50% of the distance between the anterior
superior iliac supine and the superior border of the patella
and on the biceps femoris muscle for the knee flexors at 50% of
the distance between the ischial tuberosity and the lateral
epicondyle of the tibia. The ground electrode was placed
on the tibial tuberosity. Prior to electrode placement, an
approximate 8 × 8 cm area on each electrode application site
was cleaned with an isopropyl alcohol pad.

Signal Processing

During each MVIC, torque and EMG signals were sampled
at 2 kHz with a data acquisition unit (MP150; AcqKnowledge
v5.0.1; Biopac Systems Inc.) and stored on a laboratory
computer for further analysis.

The torque and EMG signals were then processed offline
using a custom-written software program (LabView 2016:
National Instruments, Austin, TX). Torque signals were
scaled to units (Nm) using a regression formula and then
filtered with a fourth-order zero phase lag Butterworth filter
at a low-pass cutoff frequency of 10 Hz2,31,32. The raw EMG
signals were bandpass filtered at 20-400 Hz using a zero-
phase fourth-order Butterworth filter and subsequently
rectified3,31,32. All subsequent analyses were conducted on
the scaled and filtered signals.

Torque onset was determined as the point when the
torque signal reached 7.5 Nm for the knee extensors and 4
Nm for the knee flexors3,32,33. EMD was determined as the
time difference (ms) between the EMG and torque onsets
(Figure 1)3. The EMG onset was determined manually by
visual inspection where the EMG signal first deflected from
Peak EMG was determined as the highest EMG amplitude value of the filtered EMG-time curve during each participants' MVIC. EMG RMS was quantified at time intervals of 0-50 ms (RMS\(_{50}\)), 0-100 ms (RMS\(_{100}\)), 50-100 ms (RMS\(_{50-100}\)), and 0-200 ms (RMS\(_{200}\)) from EMG onset. RER (% peak EMG×s\(^{-1}\)) was used to examine the rate of muscle activation and was calculated as the linear slope of the EMG-time curve which was low-pass filtered (using a 10-Hz linear EMG envelope) and normalized to peak EMG at time intervals of 0-30 ms (RER\(_{30}\)), 0-50 ms (RER\(_{50}\)), and 0-75 ms (RER\(_{75}\)) from EMG onset\(^5\). It has been reported that the EMG signal amplitudes tend to decrease at 80-100 ms following the signal onset\(^5\); therefore, the current study used the aforementioned time periods (i.e., 30, 50 and 75 ms) to measure RER\(^{31}\).

Statistical Analysis

We conducted separate three-way repeated-measures analyses of variance [ANOVA; muscle (knee extensors and flexors) × limb (dominant and non-dominant limb) × time (pre-season, mid-season, and end of the season)] to analyze the EMG RMS, RER, and EMD variables. When appropriate, follow-up analysis included one-way repeated measures ANOVAs, Tukey-Kramer multiple comparison post-hoc test and two-factor interaction analysis for either simple main effects (when a significant interaction was present) or main effects collapsed across the opposing variable (when no significant interaction was present). Eta squared (\(\eta^2\)) effect sizes were reported for each ANOVA using the following formula\(^{34}\):

\[
\eta^2 = \frac{\text{Sums of Squares}_{\text{Effect}}}{\text{Sums of Squares}_{\text{Total}}}
\]

where 0.02, 0.13, and 0.26 were considered small, medium, and large effect sizes, respectively\(^{34}\). NCSS 2019 Statistical Software (NCSS, LLC. Kaysville, Utah) was used to analyze all data, and an alpha level of \(P \leq 0.05\) was used to determine statistical significance.

Results

No significant interactions or main effects for limb were observed for any of the EMG RMS, RER, or EMD variables \((P>0.05)\). There was, however, a main time effect in which significant changes were observed for EMG RMS at 0-50 ms \((F_{2,24}=4.27, P=0.026)\), 0-100 ms \((F_{2,24}=5.68, P=0.01)\), and 50-100 ms \((F_{2,24}=4.99, P=0.015)\) (Table 2). Post-hoc testing showed that the EMG RMS increased at the end of the season compared to the pre-season value. The effect sizes for these differences were large \((\eta^2=0.36-0.47)\).

We did not observe a significant interaction or main effect for the RER\(_{30}\) and RER\(_{50}\) variables \((P>0.05)\). However, there was a significant interaction between muscles and time for the RER\(_{75}\) \((F_{2,24}=4.59, P=0.02)\). Post-hoc testing revealed that the knee flexor RER\(_{75}\) was significantly greater at the
mid- and end-season compared to pre-season (P<0.01; Figure 2). Knee extensor RER\textsubscript{75} did not statistically increase over time (P>0.05). The effect size for this difference was large (η²=0.81).

Although there was no three-way interaction observed for EMD (P>0.05), a significant interaction between muscles and time was observed (F\textsubscript{2,24}=6.03, P<0.01). Post-hoc testing revealed that the EMD significantly decreased at mid-season and at the end of the season compared to pre-season for the knee flexors (P<0.001, Figure 3); however, there were no significant differences in EMD between time points for the knee extensors (P>0.05, Figure 3). EMD was also significantly

mid- and end-season compared to pre-season (P<0.01; Figure 2). Knee extensor RER\textsubscript{75} did not statistically increase over time (P>0.05). The effect size for this difference was large (η²=0.81).

Although there was no three-way interaction observed for EMD (P>0.05), a significant interaction between muscles and time was observed (F\textsubscript{2,24}=6.03, P<0.01). Post-hoc testing revealed that the EMD significantly decreased at mid-season and at the end of the season compared to pre-season for the knee flexors (P<0.001, Figure 3); however, there were no significant differences in EMD between time points for the knee extensors (P>0.05, Figure 3). EMD was also significantly
longer for the knee flexors than the knee extensors at the pre-
season time point ($P<0.05$). The effect size for the difference
in the knee flexor EMD was large ($\eta^2=0.95$).

**Discussion**

The purpose of the current study was to examine muscle
activation characteristics for the knee extensors and flexors in
collegiate women’s soccer players before (preseason), during
(mid-season), and at the end (end-season) of the competitive
soccer season. The primary findings in the current study
showed that EMG RER\textsubscript{75} of the knee flexors and mean EMG
RMS collapsed across muscle (0-50, 0-100, and 50-100 ms)
were significantly increased at the mid- and/or end-season
compared to the preseason. In addition, knee flexor EMD was
significantly reduced at the mid-season and remained lower
at the end of the season. The increase in EMG RMS and knee flexor RER\textsubscript{75} in the
current study could be a result of the soccer-specific activity
and strength training performed by the soccer players
during the competitive season\textsuperscript{5,35}. Previous research has
shown that a 14-week heavy-resistance strength training
program for non-athletes increased knee extensor RER
values by approximately 41-106\%\textsuperscript{5}. Although the present
study did not observe significant knee extensor differences
across a competitive soccer season (which could be due to
low statistical power), it is interesting to point out that the
present study observed significant increases in EMG RER\textsubscript{75}
for the knee flexors. Cutsem et al.\textsuperscript{35} also reported that
average EMG (0-30, 0-50, and 0-100 milliseconds) and RER
(0-30, 0-50, and 0-75 milliseconds) of the ankle dorsiflexors
were enhanced after a 12-week lower-leg dynamic strength
training program. Similarly, the present study found a ~35-
45% improvement in early EMG RMS of the knee extensors
and flexors (collapsed together) and knee flexor RER\textsubscript{75} at
the mid and end-season compared to the pre-season (Table
2 and Figure 2). It is interesting to note that the increase in
EMG RMS and RER observed in the present study occurred
within the 0-100 millisecond time period. This finding, which
is in line with the results of previous research\textsuperscript{5} may suggest
that the soccer-specific activity and muscle strength training
performed by the soccer players in the present study were
effective at increasing the neural drive and neuromuscular
activity of the leg extensors and flexors during the early
phase of muscle activation.

Another notable finding of this study was that EMD of the
knee flexor muscles decreased significantly from the pre-
season (115.44 ms) to the mid- (79.64 ms) and end-season
time points (80.75 ms). We also observed a significantly
longer EMD for the knee flexors compared to the knee
extensors at pre-season (Figure 3). This is consistent with
the findings of Hannah et al.\textsuperscript{36} who also found longer baseline
EMD values for the knee flexors (hamstrings) than the knee
extensors (quadriceps) in healthy, college-aged males. It
should be noted that although a significant decrease in EMD
for the knee flexors was observed in the present study, we
did not observe a decrease in EMD for the knee extensors.
In contrast, Kubo et al.\textsuperscript{37} reported a decrease in knee
extension EMD values of 18.4\% after a 12-week isometric
knee extension strength training program in recreationally
active college-aged adults. Additionally, Wu et al.\textsuperscript{17} showed
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A knee extension EMD reduction of 12.2% after 8 weeks of plyometric training (total 16 training sessions) in college-aged males. The discrepancies between these findings and those observed in the present study may be due to differences in the types of training activities performed and/or the athletic status of the participants that were tested. For example, the present study examined highly-trained female athletes that performed both in-season strength training and soccer-specific activity whereas the previous studies examined non-athlete participants that only performed strength or plyometric training. Previous research has reported that decreases in EMD after training may be due to increases in muscle stiffness\(^3\). In-season performance training combined with sport-specific activity has been shown to elicit significant increases in stiffness for the hamstrings\(^5\) but not for the other muscles and structures of the lower-body (i.e. leg stiffness\(^3\)). Thus, the possibility of training-induced increases in muscle stiffness specifically for the hamstrings may explain why EMD characteristics of the knee flexors were improved to a greater degree than those of the knee extensors in the present study.

Our findings of a significant increase in EMG RMS and RER and a decrease in knee flexor EMD may contribute to improvements in rapid muscle strength characteristics (i.e., RTD, RTD/PT, etc.)\(^6,7\), which could increase soccer-specific performance and reduce the risk of injury. Previous literature has reported increases in relative rapid strength values across a competitive soccer season in female soccer players\(^8\), which could be linked to increases in neural activation characteristics, as was reported in the present study (Figure 4). An increase in the amount of force produced within a short time period (<100 milliseconds) during soccer-

**Figure 4.** Relationships between the percent change (%Δ from preseason to end-season) in rate of torque development at 0-100 milliseconds (RTD\(_{100}\)) and (A) rate of EMG rise at 0-75 milliseconds (RER\(_{75}\)) and (B) EMG root mean square at 0-100 milliseconds (RMS\(_{100}\)) for the knee flexors. The RTD data used in the figure were derived from the torque signals produced by the same soccer players in a previously published study by Akehi et al.\(^9\).
specific activity may provide for better knee joint stabilization and a lower risk of knee ligamentous injuries such as non-contact anterior cruciate ligament (ACL) tears. These findings may have important implications for athletes, and in particular female athletes since they are more susceptible to ACL tears and other knee-related injuries. Previous research suggests that a non-contract ACL injury may be due to several different mechanisms including reduced hamstring activation, slower muscle contraction time, decreased knee flexion range of motion, and greater valgus angle at the knee. When considering the aforementioned mechanisms for knee ligamentous injuries, an increase in rapid activation of the knee flexors, as was observed in the present study, may be a key component in reducing an athlete’s risk of injury during a competitive soccer season. Finally, it should be noted that no significant effects for limb were observed for any of the EMG RMS, RER, or EMD variables measured in this study. These findings suggest the absence of neural activation differences between the dominant and non-dominant legs, which may be an important factor in preventing lower-extremity injury.

In conclusion, our findings demonstrated increases in EMG RMS of the knee extensors and flexors and knee flexor RER75 and decreases in EMD of the knee flexors across a competitive season in collegiate women’s soccer players. These improvements may be attributed to motor unit behavioral enhancements and/or other noncontractile structure changes as a result of the strength training and sports-specific activity performed during the season. These changes may ultimately enhance the muscle contractility and rapid force production capabilities of the athletes when playing soccer. We did not observe any negative changes across the season, which suggests that the in-season strength and soccer-specific activity was not overly extensive or fatiguing. Because the soccer players in this study performed both soccer-specific activity and strength training during the season, it is difficult to attribute one or the other (soccer-specific activity or strength training) as the primary reason for our results. We can only speculate as to why certain variables increased or decreased. In the present study, we had a limited amount of time to test subjects at each point during the season because of strict training schedules, team practice, and games. Thus, we could not control for the menstrual cycle of the subjects in our study. Nevertheless, previous research has shown no significant changes in EMD, force, or rate of force production characteristics across the menstrual cycle in young women. Therefore, based on this research, it is unlikely that variations in the menstrual cycle had a substantial effect on the neuromuscular properties of our subjects. The findings in the present study highlight the need for future research to examine the neuromuscular property changes that occur across other sports seasons, including basketball, baseball, and track and field. Such research may help in the development of in-season strength and sport-specific training programs aimed at improving neuromuscular performance and reducing the risk of musculoskeletal injury in athletes who participate in these sports.

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