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Title Page

Head Impact Exposure in Hawaiian High School Football: Influence of Adherence Rates on a Helmetless Tackling and Blocking Training Intervention

Corresponding Author:
Erik E Swartz, PhD, ATC, FNATA
Vice Dean & Ruth S. Ammon Professor
School of Health Sciences, Ruth S. Ammon College of Education and Health Sciences
Adelphi University
Harvey Hall 116, 1 South Avenue Garden City, NY 11530
Phone: 516.877.4094
Email: eswartz@adelphi.edu

Jay L Myers, PhD
Assistant Professor, Department of Biology
Southern New Hampshire University
j.myers2@snhu.edu

Jong Soo Lee, PhD
Associate Professor, Department of Mathematics and Statistics
University of Massachusetts Lowell
jongsoo_lee@uml.edu

Steven P Broglio, PhD, ATC, FNATA
Associate Dean, Professor, School of Kinesiology
Director, U-M Concussion Center
University of Michigan
broglio@umich.edu

Troy Furutani MS, ATC
Program Manager, Hawaii Concussion Awareness and Management Program, Department of Kinesiology and Rehabilitation Science
University of Hawai'i at Manoa
tfurutan@hawaii.edu

Ross Oshiro, MS, ATC, LMT
Program Coordinator, Hawaii Concussion Awareness & Management Program, Department of Kinesiology & Rehabilitation Science
University of Hawai'i at Manoa
oshiror@hawaii.edu

Gerard A Gioia, PhD
SCORE Program, Children's National Hospital, Professor, Depts of Pediatrics and Psychiatry
George Washington University School of Medicine

GGioia@childrensnational.org

Darian Brothers, MS, ATC
Graduate Assistant, Department of Kinesiology and Rehabilitation Science
University of Hawai'i at Manoa
darianb@hawaii.edu

Kiera Glodowski, MS, ATC
Graduate Assistant, Department of Kinesiology and Rehabilitation Science
University of Hawai'i at Manoa
kierag27@hawaii.edu

Ivet Lloansi, MS, ATC
Graduate Assistant, Department of Kinesiology and Rehabilitation Science
University of Hawai'i at Manoa
illoansi@hawaii.edu

Lauren Meyer, ATC
Graduate Assistant, Department of Kinesiology and Rehabilitation Science
University of Hawai'i at Manoa
meyerlk@hawaii.edu

Nathan Murata, PhD, ATC
Dean, College of Education
University of Hawai'i at Manoa
nmurata@hawaii.edu

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Head Impact Exposure in Hawaiian High School Football: Influence of Adherence Rates on a Helmetless Tackling and Blocking Training Intervention

Abstract

Context High school football remains a popular, physically demanding sport despite the known risks for acute brain and neck injury. Impacts to the head also raise concerns about their cumulative effects and long-term health consequences.

Objective To examine the effectiveness of a helmetless tackling training program to reduce head impact exposure in football participants.

Design A three-year, quasi-experimental, prospective cohort (clinicaltrials.gov #NCTXXX) study.

Setting Honolulu (XXX, XXX) area public and private secondary schools with varsity and junior varsity football.

Patients or Other Participants Football participants (n=496) ages 14 to 18 years old.

Intervention(s) Participants wore new football helmets furnished with head impact sensor technology. Teams employed a season-long helmetless tackling and blocking intervention in Years 2 and 3 consisting of a 3-phase, systematic progression of 10 instructional drills.

Main Outcome Measure(s) Head impact frequency per athlete exposure (ImpAE), location, and impact magnitude per participant intervention adherence levels (60% and 80%).

Results An overall regression analysis revealed a significant negative association between ImpAE and adherence (p=0.003, beta=-1.21, SE=0.41). In year 3, a longitudinal data analysis of weekly ImpAE data resulted in an overall difference between the adherent and non-adherent groups (p=0.040 at 80%; p=0.004 at 60%), mainly due to decreases in top and side impacts. Mean cumulative impact burden for the adherent group (n=131: 2,105.84g ± 219.76,) was significantly (p=0.020) less than the non-adherent group (n=90: 3,158.25g ± 434.80) at the 60% adherence level.

Conclusions Participants adhering to the intervention on at least a 60% level experienced a 34% to 37% significant reduction in the number of head impacts (per exposure) through the season. These results provide additional evidence that a helmetless tackling and blocking training intervention (utilizing the HuTT® program) reduces head impact exposure in high school football players. Adherence to an intervention is crucial for achieving intended outcomes.

Keywords: athletes, brain, neck injuries, prospective studies, outcome assessment

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Key Points

- Participants adhering to the intervention on at least a 60% level experienced a 34% to 37% significant reduction in head impacts by the end of the season compared to those who did not adhere to the intervention at least 60% of the time.
- Football players who engaged in helmetless tackling training at a frequency of 2 times per week (24 sessions over 12-week season) were likely to benefit from fewer head impacts and the associated reduction in impact force burden (i.e., g's: gravitational acceleration).
- Adherence to any type of intervention, whether it be exercise, behavioral, or medical, is crucial for achieving intended outcomes.

Introduction

High school football remains highly popular, with approximately one million participants across the USA in all versions of the sport (i.e., 11, 9, 8, 6 player).[1] American football is generally considered a collision sport, with a high incidence of injuries, including serious or catastrophic head or neck injuries.[2] Additionally, football participants can sustain hundreds of head impacts in a season .[3–6] The cumulative effects (i.e., burden) of these head impacts, whether having resulted in a concussion or not, are thought to be associated with long term health consequences[7–9], although not all research findings support this conclusion[3,10].

To mitigate negative outcomes, a multitude of strategies have been developed and implemented with the aim of decreasing head impact exposure in the sport of football. Whether through education, issuing penalties or fines, or intervention and training techniques, these efforts typically focus on discouraging the behavior of initiating contact with the head when a participant executes a tackle or block skill.[11] Training football players in techniques for avoiding head impacts have been studied,[12–16] with some findings suggestive of effectiveness, although study quality (i.e., level of evidence) is generally low.[17] Accordingly, The National Athletic Trainers' Association recommend to "engage all stakeholders in the generation of high-level scientific research to test and validate strategies, techniques, or technologies proposed to support the reduction of head-impact exposure in football".[11] Given the potential for grave health consequences associated with head-first contact behavior, rigorous, high-level research is critical in understanding how to teach, train, and achieve mastery of contact skills, namely blocking and tackling, that reduces the risk for head impacts.

One high-level study conducted at the high school level involved a two-year randomized controlled trial testing the effectiveness of a helmetless-tackling behavioral intervention.[15] Research participants from four high school football programs underwent a season-long tackling training program performed without wearing helmets or shoulder pads during practice sessions. The investigators had coaches participate in a pre-season clinic which provided on-field demonstrations of the prescribed helmetless drills complemented with a hard copy manual and on-line video repository for them to use throughout the season. The authors reported a decrease in head impact frequency during the mid-point of the season in those randomized to the helmetless tackling training intervention. The same helmetless tackling training behavioral intervention was conducted in a smaller sample at the collegiate level and also reported a decrease in head impacts in the treatment group[14]. The underlying theory supporting the helmetless training intervention effectiveness[14] lies in the concept of risk compensation[18,19]; which is described as a change in behavior or an unintended shift in injury pattern derived from a new protective measure. In the case of football, this phenomenon is illustrated by the paradox of wearing a helmet, which allows for head-initiated contact because of the protection it affords, as in providing a false sense of security. The helmet is associated with the rise of catastrophic neck injuries due to spear-tackling behavior seen in football with the advent of the hard, outer-shell in the late 1950's.[20] While the introduction of rules in the 1970s reduced the incidence of these injuries[20], the rules themselves do not directly train or correct incorrect behavior proactively, they only provide a disincentive to exhibiting the behavior. To our knowledge, no other prospective research rooted in a helmetless-training concept exists, particularly as being deployed across an entire team versus being randomized to a smaller group within a team.

While research results investigating the effectiveness of tackling training interventions for reducing head impacts or injury in football are promising, the dosage (i.e., frequency, duration, intensity) of the intervention prescription, and more importantly participant adherence, to these interventions, is poorly described, if at all. In other words, to more fully understand whether a desired outcome is truly indicative of the actual response to the medical intervention, it is essential to know the rate to which participants actually completed the treatment. For example, the American Medical Association defines adherence as completion of at least 80% of a prescribed intervention.[22] A lower rate of adherence below a threshold would reduce one's ability to conclude the results, or intended benefit, was indeed due to the treatment. Adherence rates are not commonly reported in behavioral or exercise intervention research. In exercise intervention studies that have reported it, a 70% threshold has often been used.[23] In the helmetless tackling training research cited above[14,15], adherence was not reported, yet a minimum 60% attendance to the intervention (prescribed at a rate of one or two times per week) was used as an inclusion criteria in analyzing the results. Other research using techniques to decrease head impacts, or its associated injury, poorly describe the intervention implementation plan (i.e., intention to treat; ITT) or did not report the rate to which participants adhered to the planned intervention itself.

Early research in head impact biomechanics in football initially measured and reported on various descriptive iterations of head impact frequency, whether as an overall season average[24,25] or other measure (eg, median, quartile ranges). Others have reported the accumulated burden by including measures of linear and rotational acceleration as a way of better appreciating the potential amount of energy delivered to, and thus succumbed, by the brain[8,26] over a period of time, such as a season or career.[6,10,27] For example, Broglio et al [6] reported high school athletes to have accumulated more than 16,000g of linear acceleration in a single season. More recently, Zuidema et al[8] reported physiological impairments in oculomotor function and elevations in blood biomarker levels with astrocyte activation and neuronal injury being associated with impact burden through a season. Thus, exploring the effectiveness of a behavioral intervention for football tackling and blocking should include not only whether the number of head impacts are lowered, but to what extent this also mitigates the accumulating force burden over time.

Therefore, the purpose of this research was to study the effectiveness of a helmetless tackling training program for reducing head impact exposure in high school football participants. Head impact exposure was expressed both in terms of the frequency of head impacts (controlled by attendance), the impact location, as well as the accumulated burden (gravitational acceleration) of these impacts at the end of the season. Additionally, to more closely associate the intervention to the desired outcome of decreased head impact exposure, the data were analyzed according to the rate of intervention adherence by participants (i.e., intervention dose) to the intervention plan (ITT).

Methods

This study involved a quasi-experimental, prospective cohort design. Methods for the study were approved by the University's IRB and registered as a clinical trial (clinicaltrials.gov #NCTXXX). Over a three-year period, following approval by district and school administrators, participants were recruited from four high school football programs in the XXX, XXX area. Year 1 (2019) served as a baseline season for participant and coach familiarization and piloting data collection, whereas Years 2 and 3 (2021 and 2022, respectively) were planned for the implementation of the intervention. (Note: COVID-19 pandemic cancelled the 2020 XXX football season). Programs were comprised of two public (XXX Interscholastic Association) and two private (Interscholastic League of XXX) varsity (4) and junior varsity (2) teams representing school grades 9-12. The nature of the research was explained to participants and legal guardians in group sessions and 1:1 conversations. Subsequently, IRB approved written assent and consent forms were obtained from all participants and legal guardians, respectively.

Each participant was sized and fitted by research personnel for a new Riddell, Inc. (Elyria, OH) Speed Flex helmet as per the manufacturer's fitting criteria. Helmets were furnished with a Riddell InSite Impact Response System. The InSite System, which has been demonstrated as strongly correlated with Hybrid III acceleration data[28] and used previously in related studies,[27,29] records impact frequency, magnitude (low 10-19 g's; medium 20-28 g's, high 29-43 g's, alert 44-63 g's, and alert >63 g's), and location (front, top, back, right and left sides). Researchers monitored data capture, storage, and export to the Riddell InSite Training Tool, a password secure proprietary cloud-based system.

A helmetless tackling and blocking behavioral intervention (HuTT®; University of New Hampshire, Durham, NH) was deployed in Years 2 and 3. The HuTT® program consists of a 3-phase (i.e., Static, Dynamic, Functional), systematic progression of ten instructional drills performed without helmets and shoulder pads and is intended to develop and reinforce motor behaviors that explicitly remove the head as a point-of-contact. Intervention sessions were approximately 10 minutes in duration and consisted of a prescribed set of two drills per session. Participants executed techniques against tackling bags or a padded shield held by teammates, alternating contact from the right and left directions. Based on prior research which showed a treatment effect[15], the intervention was assigned at a frequency of four sessions per week during the pre-season and two sessions per week during the competition season. Sessions were held at the beginning or end of practice and monitored by research personnel.

The HuTT® program was delivered to research participants by the team's respective coaching staff who underwent standardized training before each of the two intervention seasons. At the outset, coaches underwent an on-boarding process consisting of a web-based textual and video formatted standard operating procedure, complemented with protocol videos and knowledge check features (i.e., quizlets; Retrieve Technologies, Manchester, NH). This was followed by virtual conference call workshops with researchers and an experienced coach consultant on a team-by-team basis to answer questions specific to a coaching staff. Coaches were also provided an abbreviated field-side manual in the form of laminated pocket cards for quick reference. In Year 3, the cessation of COVID travel restrictions allowed for an intensive 3-hour on-site training of coaches by research personnel and experienced coach consultants (average of six years using the HuTT® program).

Research personnel were present on-site during the season for quality controls and field observations. The upcoming day's drills were reviewed prior to deployment and participant intervention attendance (i.e., adherence) was recorded. Detailed field notes included drill compliance (assigned drill number), drill sequencing, participant repetitions, appropriate use of field-equipment, and removal of helmets and shoulder pads. Intervention adherence was calculated as a ratio of the number of treatments completed versus the number of treatments prescribed (i.e., ITT) according to the original intervention plan (four sessions/week in the pre-season and two sessions/week in the regular season).

Daily attendance, in a game or practice session, defined as entry into any training or game when the helmet was worn regardless of duration, were recorded as an athlete exposure (AE). Time sequences of athlete exposures was tracked and included start/stop times for the overall session as well as for pre-game, quarters, and half-time of scrimmage and game sessions. Raw data were exported in aggregate and reviewed at various intervals throughout the season for purposes of quality control. Before final interpretation, these data were filtered for noise and spurious impacts using athlete exposure time sequences and attendance records.

Data were processed in spreadsheet format for corresponding head impact frequency counts, acceleration (g's) levels, and impact location across each week of the season. Dependent variables included: head impacts per athlete exposure (ImpAE; head impact frequency divided by attendance), location of head ImpAE, and head impact burden (the sum of accumulated head impact frequency per impact location and the assigned median gravitational acceleration level). Independent variables included grouping participants according to their adherence rate on two levels (80%, 60%), and time (weeks).

Sample Size Determination and Statistical Analysis

When designing the study, we executed sample size and power calculations for the two-sample t-tests for the mean differences in head impacts per exposure between hypothetical treatment and control groups. With a sample size of 100 (50 in both the treatment and control groups) and a mean difference of 1.2 and the standard error (SE) of 2.0, such test yielded a power of 84%. Power calculations were conducted using PROC POWER in SAS (version 9.4).

A linear regression was first used to test for associations between ImpAE and adherence to the intervention. This was followed by an analysis of longitudinal data over time (week) of ImpAE by linear mixed-effects model with adherence and time effects (fixed effects), accounting for random effect of time within subject. The weekly ImpAE was also evaluated by false discovery rate (FDR) corrected t-tests at each week. Finally, an analysis of variance (ANOVA) was used to compare adherent and non-adherent groups (with alpha=0.05, and reported mean ± standard error), for overall ImpAE, location of ImpAE, and cumulative impact burdens at the conclusion of the study in Year 3. The statistical analysis of data were performed using R software.

Results

The Sample

Based on the original study plan, we set out to conduct our research over three successive football seasons starting in 2019, with the intervention commencing in 2020. The 2019 data was not analyzed or reported here, since it did not involve the intervention. Unfortunately, after Year 1 the COVID-19 pandemic cancelled the 2020 season, creating a full year of inactivity between Year 1 and Year 2 (2021). Additionally, before Year 2, one of the teams discontinued participation due to low returning participants, full coaching staff turnover, and practice facility changes preventing adequate storing and maintenance of research equipment. We subsequently recruited an additional three teams (2 Varsity, 1 Junior Varsity) from two new schools, one school agreeing to commence with the intervention, the other agreeing to an initial baseline year. Year 2 also involved an 8-week cessation of all public high school in-person activities including sports (August 4th-September 24th), with sporadic daily interruptions in the private schools.

Thus, the investigation enrolled a total of 496 unique participants (male=648, female=2 over three years. Of this total, 154 accounting for >1 year participation and 19 in all three years, resulting in 650 participant-seasons. This sample exceeded our original *a-priori* estimated sample size. Attrition resulted from a combination of factors, such as graduation, departing team for personal reasons, and season ending injury. New participant recruitment between years was intended to replace the expected attrition over time. A total of 42 participants and their respective data were excluded due to incomplete enrollment paperwork or demonstrated equipment failure. The final analysis involved organizing participants' data into adherent or non-adherent groupings on the 60% and 80% adherence threshold levels, resulting in different sample sizes for each category and year the intervention was deployed (Figure 1A-D CONSORT Diagram)

The Association between Level of Adherence and Impacts

An overall regression analysis revealed a significant negative association between ImpAE and adherence ($p=0.003$, beta=-1.21, se=0.41), suggesting that the more adherent subjects were, the less ImpAE the subjects sustained. From the regression analysis of ImpAE on raw adherence, a significant negative association was found between ImpAE and adherence during Year 2 ($p=0.010$, beta= -1.43, se=0.55) and again to a greater of significance in Year 3 ($p<0.001$, beta= -2.26, SE=0.66). (Figure 2A-C)

Effect of the Intervention over Time

When the intervention began in Year 2, ImpAE comparisons between adherent and non-adherent groups were similar in weeks one through week 4 (difference in mean ImpAE of 0.139, $p=0.933$ at 80%; difference in means of 0.093, $p=0.927$ at 60%). Starting in Week 5, the two public schools' seasons were placed on a COVID pause, while the two private schools continued, albeit with variable interruptions. Thus, this timepoint shows the non-adherent group had significantly less ImpAE than the adherent group at the 60% level (difference in mean ImpAE of -1.34, $p<0.001$), yet the season and pace with the intervention were no longer synchronized, negating further comparisons of intervention effects over time. (Figure 3A-F)

In year 3, the longitudinal analysis of weekly ImpAE data shows a pattern of separation and overall difference between the adherent and non-adherent groups ($p=0.040$ at 80%; $p=0.004$ at 60%) as well as a decrease of ImpAE over time ($p=0.039$ at both 80% and 60%). The further analysis of week-by-week data revealed significantly fewer ImpAE for the adherent group when compared with non-adherent group in multiple weeks at both the 80% and 60% thresholds. (Figure 4A-F)

Overall Group Comparisons at Study's Completion

The comparison of adherent versus non-adherent group by aggregate total of ImpAE showed that participants in the adherent group (at 80%) experienced significantly ($p=0.020$) fewer ImpAE ($n=66$: 1.88 ± 0.28,) than those in non-adherent group ($n=155$: 2.84 ± 0.24). Similarly, participants in 60% adherent group had significantly ($p=0.002$) fewer ImpAE ($n=131$: 2.06 ± 0.20) than those in non-adherent group ($n=90$: 3.26 ± 0.35). (Figure 5A-B)

These Imp/AE were spread out across the four locations of the helmet [Front, Top, Side (L&R), and Back]. The comparison of adherent versus non-adherent group of ImpAE per location showed that participants in the adherent group experienced significantly fewer ImpAE than those in non-adherent group at the Top and Sides of the helmet at both the 80% and 60% levels. (Table 1)

Overall cumulative impact burden also showed that the 60% adherent group ($n=131$: 2,105.84g $\pm$ 219.76,) sustained significantly ($p=0.020$) less force over the course of the season when compared to the non-adherent group ($n=90$: 3,158.25g $\pm$ 434.80).

The cumulative impact burden each player experienced on average with just front, top, and side locations combined showed the adherent group ($N=131$: 2,105.84g $\pm$ 219.76,) sustained significantly ($p=0.020$) less cumulative impact burden than the non-adherent group ($N=90$: 3,158.25g $\pm$ 434.80) at the 60% adherence level. Distribution of cumulative impact burden by location showed no difference between adherent and non-adherent groups at either level when combining only front and top locations. However, when analyzing only side impacts, the 80% adherent group experienced significantly less ($p=0.022$) force burden ($n=66$: 634.52g ± 98.32,) compared to the non-adherent group ($n=155$: 1220.40g ± 249.23).The 60% adherent group also had significantly less ($p=0.026$) force burden ($n=131$: 827.99g ± 98.32,) than the non-adherent group ($n=90$: 1,361.94g ± 249.23) (Figure6A-F).

Discussion

This study provides additional evidence that a helmetless tackling and blocking training intervention utilizing the HuTT® program reduces head impact exposure in high school football players. Our most important finding was that participants, adhering to the intervention on at least a 60% level, experienced a 34 to 37% reduction in the number of head impacts (per exposure) by the end of the season. In practical terms and over a season comprised of at least 58 exposures (practices and games), this result equates to 56-70 fewer impacts to the head and a 33% reduction (1,053g's) in impact magnitude by the end of the season. Thus, football players who engaged in helmetless tackling training at a frequency of 2 times per week (24 sessions over 12-week season) were likely to benefit from fewer head impacts and the associated reduction in impact force (i.e., g's: gravitational acceleration) burden.

The data were analyzed according to two levels of adherence, and the results merit careful interpretation. Specifically, differences between the adherent and non-adherent groups were typically stronger at the 60% level compared to the 80% level, both numerically and statistically, yet this finding should not be interpreted to mean that fewer exposures to the treatment led to a stronger outcome. Rather, these differences were most likely because the lower threshold level (60%) increased the sample size since more participants met the lower threshold criteria than the higher level (80%).

Nagpal et al[23] recently described four possible scenarios for interpretations of exercise intervention studies that can be drawn based on variations in adherence levels and outcomes. While the scenarios typically involve comparisons between treatment and control groups, the authors suggest that results of single studies, like this one, and fitting any scenario should be interpreted with caution as there may be confounding variables (e.g., population characteristics, study environment) that can influence adherence or the outcome. This suggests that evaluating the impact of an intervention on health outcomes should arise from the context of systematic reviews that synthesize similar study designs.

Until then, at least three studies[14,15] have now tested the effectiveness of a helmetless tackling training technique across various populations and environments and each show positive outcomes from the intervention. The first investigation expressly testing the effectiveness of a helmetless tackling intervention was conducted in a single collegiate sample.[14] Twenty-five participants were randomized on the individual level within the team to undergo the helmetless tackling training program twice in the pre-season and only once in the regular season. The treatment group experienced significantly fewer head impacts per exposure than the control participants, as well as compared against their own pre-season level of head impacts per exposure. On the high school level, participants were again randomized and within four different teams.[15] Results from that two-year study found the treatment group experienced fewer head impacts per exposure compared to the control group, but only during the mid-point of the season. In other words, while the groups were similar at the pre-season, their impacts per exposure separated during the mid-season, but returned to being similar towards the end of the season. This study is the first to test the effectiveness of the helmetless tackling training program across an entire team, with grouping according to variable levels of adherence as opposed to a true control sample. The ability to affect, and statistically detect, a change given the relatively narrow overall impact per exposure margin in our sample is encouraging. In the prior research exploring the effectiveness of a helmetless tackling intervention, control subjects on the high school level experienced nearly six Imp/E, depending on the week of the season, with 10 Imp/E during games.[15] In the smaller collegiate sample[14], control subjects averaged almost 14 Imp/E. Whereas our study, non-adherent participants experienced only around 2.2-3.2 Imp/E.

It is important to appreciate not only the overall frequency of impacts sustained by high school football players during play, but also the magnitude (e.g., acceleration), that these impacts entail. Research is increasingly focused on the accumulated burden these impacts impart to the human brain over time and the potential for neurological consequences.[10,27,30] Not only did the participants in our study who were adherent to the intervention have fewer head impacts per exposure, they also experienced less accumulated force burden over time. Extrapolated out over a 4-year high school career, the magnitude of this outcome of potentially thousands less gravitational acceleration units directed to the brain[31], is substantial.

Relatedly, when focusing on the areas of the helmet most related to the behavior of leading with the head (i.e., top, front, sides),[11] it is encouraging that the decrease in head impacts was driven by significant decreases in impacts to the top and side of the helmet (as opposed to if they had been to the back of the helmet). Future research can help elucidate further whether the benefits of the training come not only in reducing overall impacts to the head, but in shifting impacts away from the top and front of the helmet.

It should be noted that the data reported herein was collected during unexpected challenges born from the COVID-19 pandemic, directly affecting the fluidity of our intended research, as others involved in clinical-intervention based studies have reported.[32] For example, faced with an inability to do an in-person training prior to the 2021 (Year 2) as we had intended, we were forced to pivot to using virtual platforms as a way to communicate and educate coaches with the intervention season.[33] While the advantages to using technology were necessary and allowed us to initiate the intervention in that year, coach on-boarding and subsequent intervention deployment was disadvantaged at the same time. Relatedly, there was unanticipated variation in coach compliance in Year 2, in contrast to previous research where teams were fully compliant.[14,15] In fact, one of our teams decided to allow individual positional coaches to carry out the intervention with their assigned skill group and on their own weekly schedule leading to a variable dosing pattern and subsequent player adherence rates. Participant related issues were also a factor associated with the pandemic interruption. The increase of community infection rates triggered a return to remote learning for public schools and an eight-week suspension of interscholastic sports. Whatever was gained in consistency for research participants across teams, was disrupted due to the priorities of public health administration during the pandemic. Finally, returning to sports participation also required proof of vaccination for participants which introduced variation in overall attendance as well as with the intervention. In Year 3, however, we were able to carry out the in-person training with an initial training and on-boarding clinic held approximately two months in advance of pre-season, allowing for more time for coaches to plan for the intervention implementation. This no doubt contributed to the stronger findings and statistical differences in our variables of interest in the final year.

In conclusion, further research is needed to better understand what intervention (drill type & technique) and player characteristics (age, maturation, experience), and intervention dosing (frequency, duration, intensity) should be used to garner the strongest response whether across a full team or specific to an individual player. Ultimately, the association with decreasing head impact behavior and improved clinical outcomes based on rigorous study design is critically needed to protect and promote life-time participation in sports or recreational endeavors.

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Legends to Figures

Figure 1. CONSORT Flow Diagram across 3 football seasons, Years 1-3 (2019, 2021, 2022), with participants from a total of six teams. Data from Year 1 are not reported in this paper. B. Participant Summary. C Data Exclusions D. Adherence.

Figure 2. Regression Plots for Adherence and Head Impacts per Athlete Exposure (ImpAE). A. Overall combined data from Years 2 and 3. B. Year 2 only. C. Year 3 only.

Figure 3. Effect of the Intervention over time for Year 2. A-B. Weekly Head Impacts per Athlete Exposure (ImpAE) used for linear mixed-effects model comparison between adherent and non-adherent groups at 60% and 80%. B-C. Mean difference between groups at 60% and 80%. D-E. False discovery rate (FDR) corrected t-test p value result at each week at 60% and 80%, dotted line indicates threshold of .05. Non-adherent group ImpAE was significantly less than Adherent group ImpAE at week 5. Note the dotted line and “x” symbol in the X-axis at week 5 indicates when two public school teams resumed the season after an 8-week COVID-19 pause.

Figure 4. Effect of the Intervention over time for Year 3. A-B. Weekly Head Impacts per Athlete Exposure (ImpAE) used for linear mixed-effects model comparison between adherent and non-adherent groups at 60% and 80%. B-C. Mean difference between groups at 60% and 80%. D-E. False discovery rate (FDR) corrected t-test p value result at each week, dotted line indicates threshold of .05. Adherent group ImpAE was significantly less than the Non-adherent group ImpAE in weeks 2, 4, 8, and 11 when grouped at 80% adherence, and all weeks except 6, 9, and 10 when analyzed at 60% level.

Figure 5. Mean Head Impacts per Athlete Exposure (ImpAE) in final season (Year 3). A. Year 3 at 60%. Participants in the adherent group had significantly (p=0.020) fewer ImpAE than those in non-adherent group B. Year 3 at 80%. Participants in adherent group had significantly (p=0.002) fewer ImpAE than those in non-adherent group.

Figure 6. Mean Cumulative Head Impact Burden in final season (Year 3). A. Front, top, side impacts combined at 80%. B. Front, top, side impacts combined at 60%. Adherent group sustained significantly (p=0.020) less cumulative impact burden than the non-adherent group. C. Top and side impacts only at 80%. D. Top and side impacts only at 60%. E. Side impacts only at 80%. Adherent group had less (p=0.022) cumulative impact burden than the non-adherent group. F. Top Side impacts only at 60%. Adherent group had less (p=0.026) cumulative impact burden than the non-adherent group.

A: CONSORT Flow Diagram

Year	Participants	Teams	Total	Freshman	Sophomore	Junior	Senior
			Participants per Team				
1	178	A	48	3	10	24	11
		C	60	2	12	27	19
		D	70	27	43	0	0

Baseline: head impact biomechanical data collected without the intervention

Year	Participants	Teams	Total	Freshman	Sophomore	Junior	Senior
			Participants per Team				
2	241	B*^	42	0	6	11	25
		C^	73	9	12	29	23
		D^	56	38	17	1	0
		E	42	3	7	19	13
		F	28	11	17	0	0

^ Intervention: Helmetless Tackling Training (HuTT®) program applied at team level

* Team B replaced Team A

Year	Participants	Teams	Total	Freshman	Sophomore	Junior	Senior
			Participants per Team				
3	231	B	39	5	7	16	11
		C	57	2	12	17	26
		D	51	11	32	5	3
		E	52	0	9	24	19
		F	32	23	9	0	0

All teams applied the Helmetless Tackling Training (HuTT®) program

B: Participation Summary

Year	Participants	1st	2nd	3rd
		Participant Years in Study		
1	178	178		
2*	241	199	42	
3	231	119	93	19

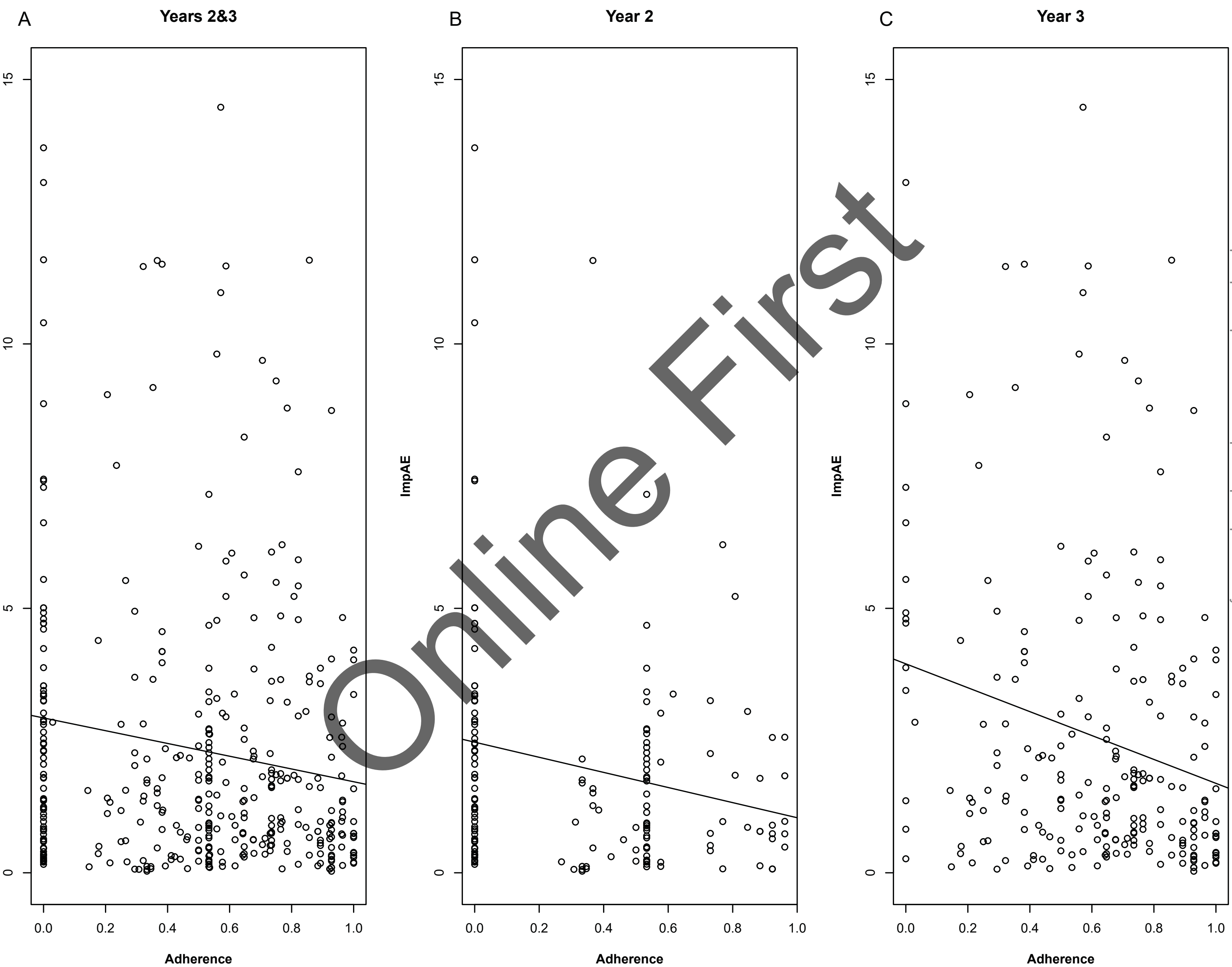
* Covid-19 cancelled the season between years 1 and 2.

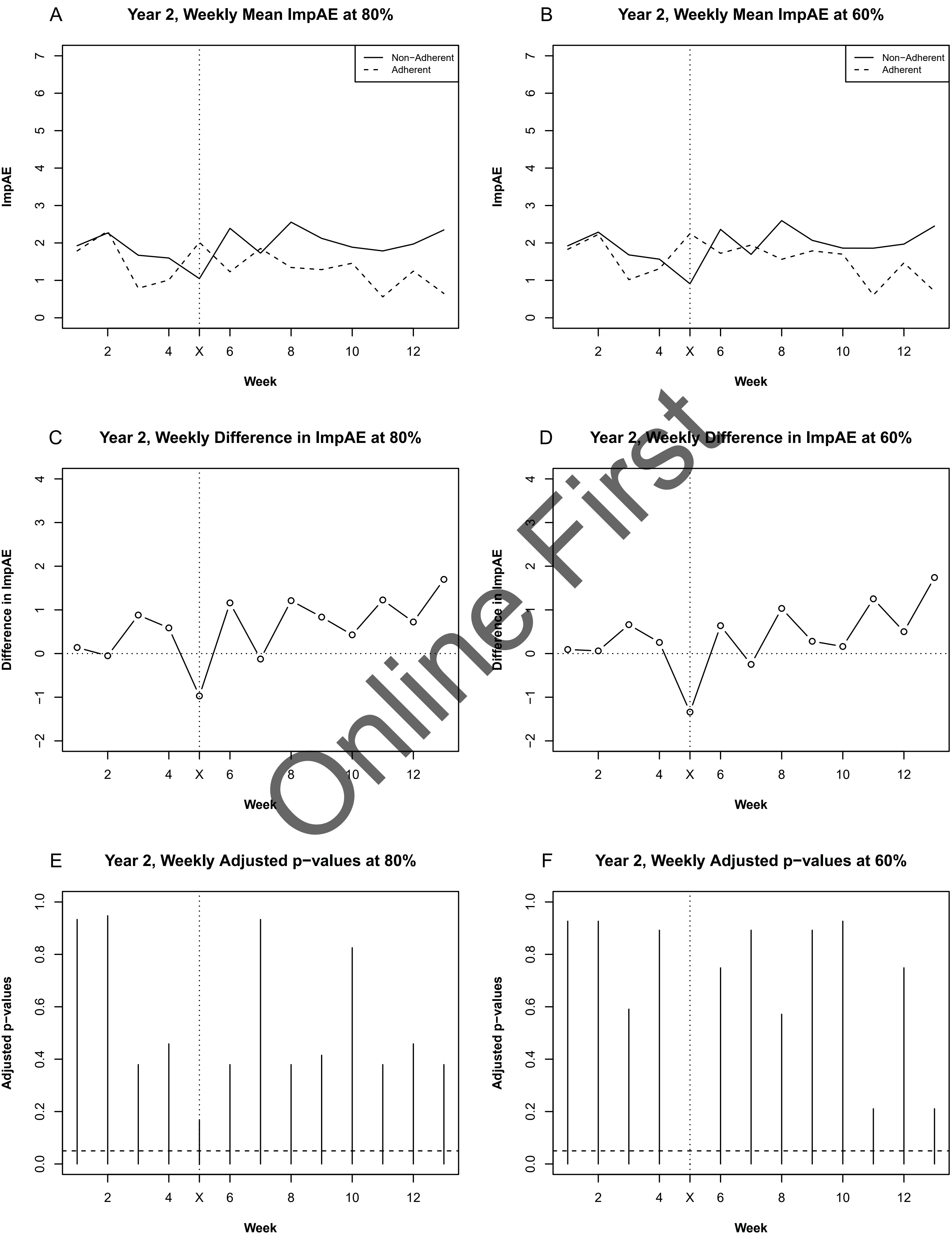
C: Data Exclusions

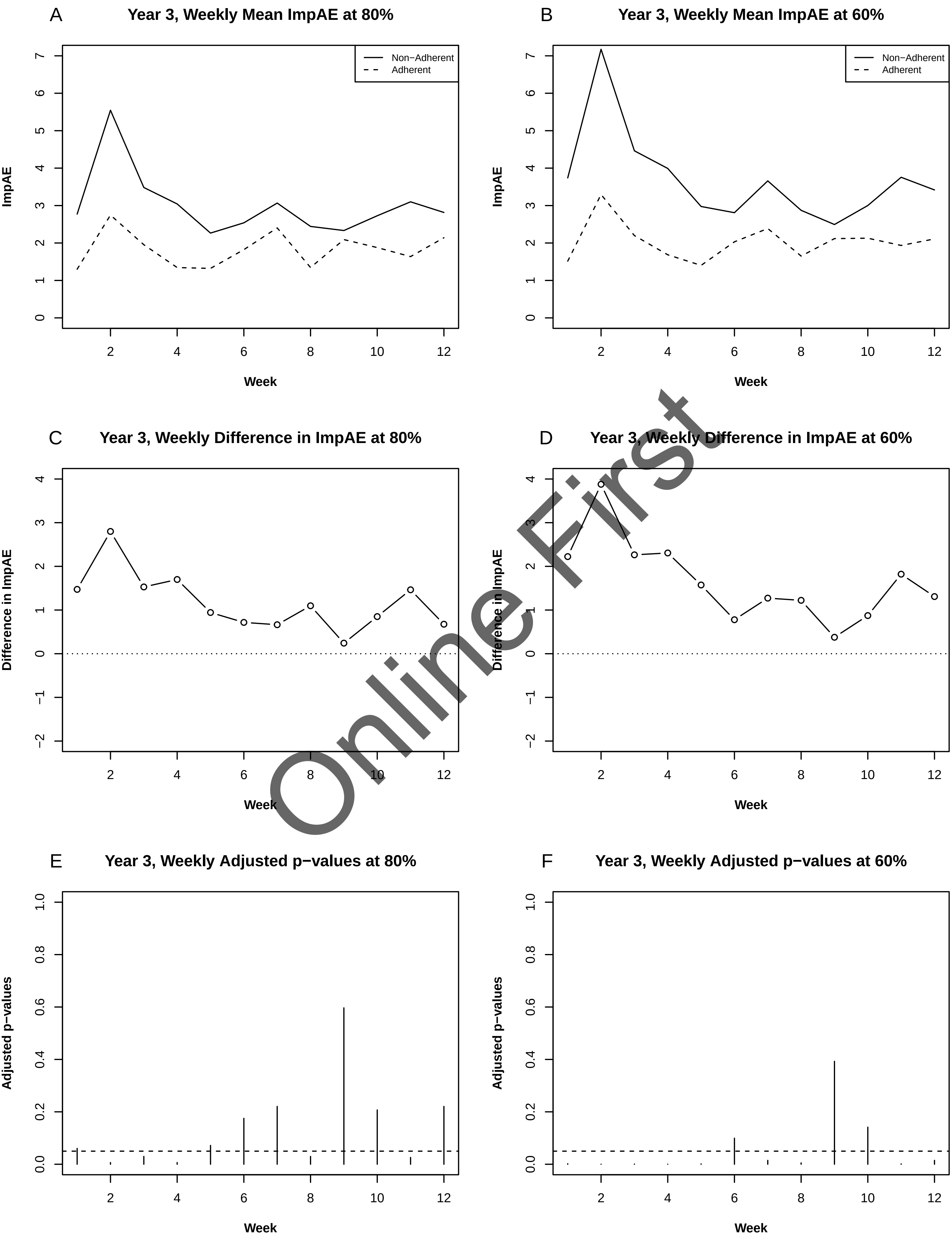
Year	Participants	Fr	Soph	Jr	Sr
1	7	7	0	0	0
2	25	6	19	0	0
3	10	0	10	0	0

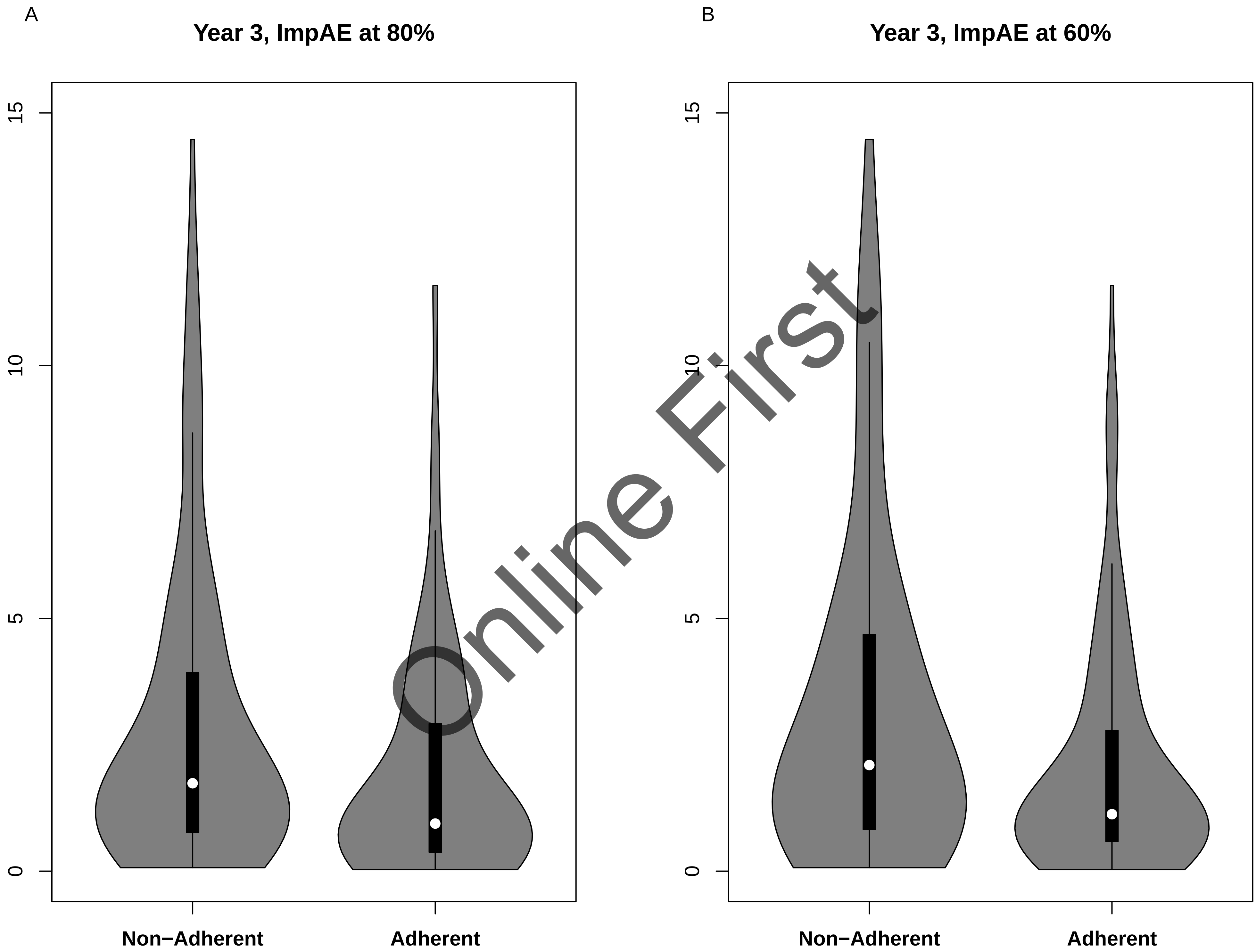
D: Adherence

Year	Threshold	Group	Total	Offense	Defense
				Percent (%)	
2	60%	Adh	28	46	54
		NonAdh	124	40	58
	80%	Adh	19	58	42
		NonAdh	133	39	59
3	60%	Adh	131	55	44
		NonAdh	90	49	49
	80%	Adh	66	61	36
		NonAdh	155	49	50


A
Years 2&3
B
Year 2
C
Year 3
ImpAE
Adherence
0
5
10
15
0.0
0.2
0.4
0.6
0.8
1.0


A
Year 2, Weekly Mean ImpAE at 80%
B
Year 2, Weekly Mean ImpAE at 60%
Non−Adherent
Adherent
ImpAE
Week
C
Year 2, Weekly Difference in ImpAE at 80%
D
Year 2, Weekly Difference in ImpAE at 60%
Difference in ImpAE
E
Year 2, Weekly Adjusted p−values at 80%
F
Year 2, Weekly Adjusted p−values at 60%
Adjusted p−values
2
4
X
6
8
10
12


A
Year 3, Weekly Mean ImpAE at 80%
Non−Adherent
Adherent
ImpAE
Week
B
Year 3, Weekly Mean ImpAE at 60%
Non−Adherent
Adherent
ImpAE
Week
C
Year 3, Weekly Difference in ImpAE at 80%
Difference in ImpAE
Week
D
Year 3, Weekly Difference in ImpAE at 60%
Difference in ImpAE
Week
E
Year 3, Weekly Adjusted p−values at 80%
Adjusted p−values
Week
F
Year 3, Weekly Adjusted p−values at 60%
Adjusted p−values
Week


A
Year 3, ImpAE at 80%
B
Year 3, ImpAE at 60%
0
5
10
15
Non−Adherent
Adherent

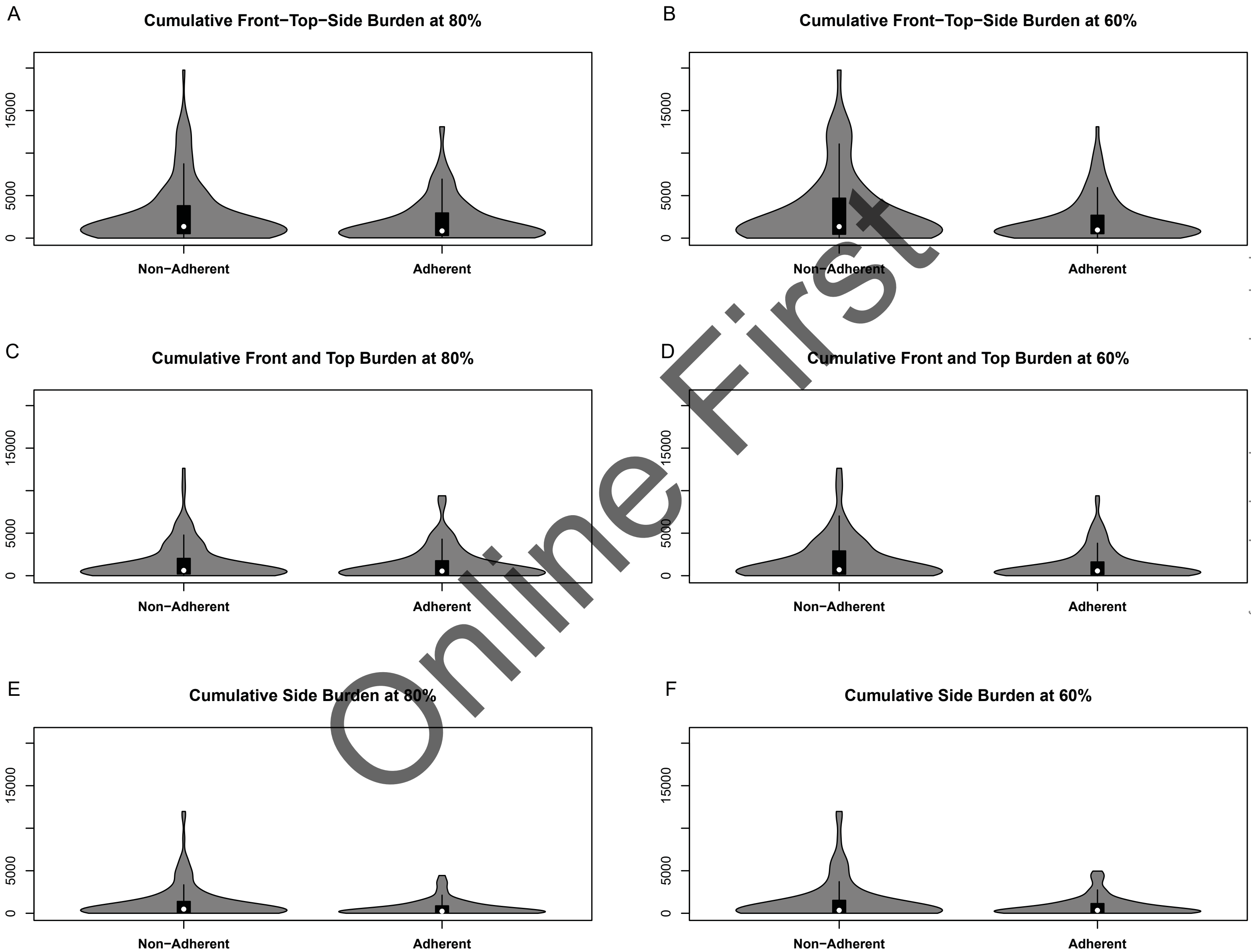

A
Cumulative Front−Top−Side Burden at 80%
B
Cumulative Front−Top−Side Burden at 60%
C
Cumulative Front and Top Burden at 80%
D
Cumulative Front and Top Burden at 60%
E
Cumulative Side Burden at 80%
F
Cumulative Side Burden at 60%
0
5000
15000
Non−Adherent
Adherent

Table 1. Head ImpAE by Location Mean (SE)

ImpAE	80% Adh	80% NonAdh	80% *P* value	60% Adh	60% NonAdh	60% *P* value
Total	1.88 (0.28)	2.84 (0.24)	0.020[a]	2.06 (0.19)	3.26 (0.35)	0.002[a]
Front	0.78 (0.17)	0.63 (0.08)	0.369	0.59 (0.10)	0.80 (0.13)	0.195
Top	0.29 (0.06)	0.83 (0.11)	0.002[a]	0.50 (0.08)	0.92 (0.16)	0.012[a]
Sides	0.54 (0.10)	1.14 (0.13)	0.004[a]	0.72 (0.09)	1.31 (0.20)	0.003[a]
Back	0.27 (0.05)	0.20 (0.02)	0.208	0.24 (0.03)	0.19 (0.03)	0.279

[a] indicates significantly fewer ImpAE comparing Adherent (Adh) to NonAdherent (NonAdh)