# Impact of Usage and Storage Pressurization on Tennis Ball Bounce

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Tennis is a sport that has been around for hundreds of years. Like many other sports, a particular type of ball is required in order to play. However, what sets tennis about from all other sports is that a tennis ball's life span is significantly shorter than any other sports ball due to its fragile and air-porous outer layer. The necessity of a tennis ball to expand and contract upon racket impact as well as firmly bounce upon making contact with the ground requires the ball to maintain a certain level of internal pressurization. While tennis balls are packed and stored in cans pressurized at a strength of 14 psi, the moment they are exposed to the earth's atmosphere they begin to slowly lose that pressure slowly but surely until they are "dead" and can no longer bounce enough to be suitable for play. Along with this constant, natural depressurization, there is the actual usage of the ball which, depending on the skill and strength of the players involved, will unnaturally deteriorate even further. With the two main causes of tennis ball deterioration known and noticeable even to amateur tennis players, the question becomes whether or there is something that can be done to artificially increase the life span of a tennis ball. While of course there isn't much that can be done to slow the effects of play on the ball besides perhaps swinging and missing more often, the idea of negating the effects of natural depressurization on a ball is an interesting one. There are non-pressurized tennis balls that exist which will significantly prolong the ball's life span; however they are heavier, don't spin as much, and are simply not suited for match play but rather relegated to a fringe practice option. A newer, more exciting countermeasure is the idea of recreating the pressurized storage container that the balls were originally packaged in. If the internal pressure of the storage container can be set at a constant 14 psi, would this be able to lessen or even nullify the effects of the ball being used? The goal of this experiment is to answer that question by comparing the effects of both usage and storage method of tennis balls to the bounce height over a period of time.

The International Tennis Federation defines a "valid" tennis ball as having a bounce height of between 53-57 inches when dropped onto a concrete (standard outdoor tennis court material) surface from a heigh of 100 inches. Throughout this experiment, the "validness" of a particular treatment group depending on the response variable is something that was kept in mind along with its comparison to other treatment groups. In order to gather these results and draw conclusions, a replicated, balanced, 3-factor fixed effect ANOVA experiment was designed which tested 2 main factors with the inclusion of a blocking factor. The 2 main factors tested were whether or not the ball was used (Play) and whether or not the tennis balls were kept in a pressurized container (Pressure)[1]. The number of days since the containers were opened (DaysOpen) was used as a blocking factor as an attempt to mitigate any potential unknown, uncontrollable nuisance factors such as weather impact, etc[4]. To promote randomization within each of the 4 treatment groups, all 12 tennis ball (4 cans, 3 balls each) were piled together and re-separated into 4 individual groups to avoid any nuisance factor regarding the production batch of the tennis balls[2]. For ease of repeatability, the tennis balls were measured immediately following this separation/re-grouping (on Day 0) and measured each even-numbered following day through Day 8[5]. Conversely, the tennis balls whose treatment groups required play were used in hour-long playing sessions every odd-numbered day through Day 7[5]. Within each treatment group, there were 3 total replicates which were represented by the 3 total tennis balls that are present in every canister and used evenly and randomly without discrimination for the duration of each hour-long playing period[3]. As part of the requirements of testing for independence, the 12 tennis balls were tested in a random order during each of the 5 measuring sessions[2].

The measurement process consisted of a DIY setup using a tri-pod, tape (to use for markers to ensure consistency of measuring), a measuring tape, and the slo-mo camera of an iPhone[5]. By marking the outer limits of the camera frame and the placement of the tri-pod, simply setting the ball on a 100-inch high platform and pulling the platform out from under it with a string allowed the bounce height to be captured in slo-mo with the measuring tape behind it (the bottom of the ball was used as the marker for height). Before starting the experiment, 3 tennis balls (not used in the experiment) were dropped 5 times each with 14 out of 15 observations falling in the 55-56 inch range which confirmed the repeatability of the measuring process. As mentioned previously, the measuring order of the 12 tennis balls were picked at random for each testing period to ensure independence of the results[2].

Following the conclusion of Day 8 of the experiment, all 60 observations were loaded into Minitab and SAS to be used in tandem to analyze the results of the experiment and test how ball usage and storage method impact the average bounce height of tennis balls[5]. The results of the ANOVA for the full model can be seen below in Figure 1.1.

Figure 1.1

### Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Play | 1 | 2.926 | 2.9260 | 5.61 | 0.023 |
| Pressure | 1 | 62.526 | 62.5260 | 119.81 | 0.000 |
| DaysOpen | 4 | 10.865 | 2.7161 | 5.20 | 0.002 |
| Play*Pressure | 1 | 0.026 | 0.0260 | 0.05 | 0.824 |
| Play*DaysOpen | 4 | 4.944 | 1.2359 | 2.37 | 0.069 |
| Pressure*DaysOpen | 4 | 15.802 | 3.9505 | 7.57 | 0.000 |
| Play*Pressure*DaysOpen | 4 | 1.948 | 0.4870 | 0.93 | 0.455 |
| Error | 40 | 20.875 | 0.5219 | | |
| Total | 59 | 119.911 | | | |

It is immediately clear that the two factors of interest, Play and Pressure, do not have a significant interaction based on their interaction term's p-value of 0.824 which will make for easier analysis when conducting multiple comparisons tests later. Furthermore, the 3-way interaction term, Play*Pressure*DaysOpen is deemed statistically insignificant with a p-value of 0.455. While the Play*DaysOpen interaction term is not statistically significant, its p-value is not > 0.25 so it can't necessarily be pooled in with the error. The full model has an r-squared adjusted value of 74.32% meaning that 74.32% of the variation within the response variable can be explained by the 3 factors in the model. This is a fairly strong number for a full model and will likely be improved in the reduced model. Following the pooling of the Play*DaysOpen and Play*Pressure*DaysOpen interactions terms with the error, the aforementioned reduced model is shown below in Figure 1.2[8].

Figure 1.2

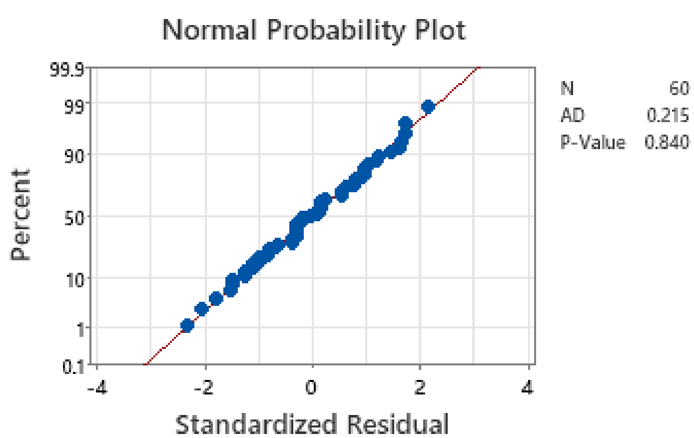
## Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Play | 1 | 2.926 | 2.9260 | 5.76 | 0.021 |
| Pressure | 1 | 62.526 | 62.5260 | 123.14 | 0.000 |
| DaysOpen | 4 | 10.865 | 2.7161 | 5.35 | 0.001 |
| Play*DaysOpen | 4 | 4.944 | 1.2359 | 2.43 | 0.061 |
| Pressure*DaysOpen | 4 | 15.802 | 3.9505 | 7.78 | 0.000 |
| Error | 45 | 22.849 | 0.5078 | | |
| Lack-of-Fit | 5 | 1.974 | 0.3948 | 0.76 | 0.586 |
| Pure Error | 40 | 20.875 | 0.5219 | | |
| Total | 59 | 119.911 | | | |

The reduced model has a r-squared adjusted value of 75.02% which is an improvement over the full model but only slightly. Furthermore, terms Play and Play*DaysOpen have slightly lower p-values in the reduced, but neither term's statistical significance designation changes based on those p-value reductions. It is also shown that DaysOpen was a good blocking factor due to its small p-value, in addition to the fact that the exclusion of the blocking factor from the model absolutely tanks its r-squared adjusted value and completely voids the results of the ANOVA. Based solely on the p-values of main factors Play and Pressure, both factors are statistically significant. However, the absolutely monstrous F-value for Pressure makes it clear Pressure is much more significant on the outcome of the response variable, Bounce, than Play.

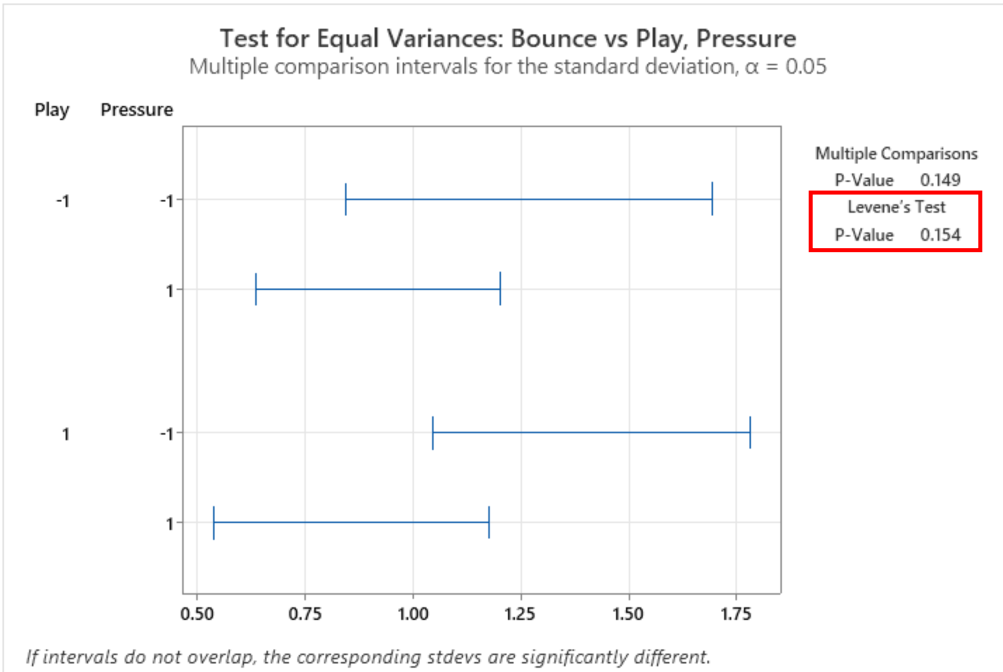
Before the mean response variables can be compared between the 2 main factors of interest, residual analysis must be performed to confirm the validity of the data and rule out any possible need for data transformation. The results of a normal probability chart are shown below in Figure 1.3[6].

Figure 1.3




A p-value of 0.840 confirms that the assumption of normality has been met[7]. Additionally, while the model's r-squared adjusted value might not have drastically changed between the full and reduced model, the normality p-value jumped from a marginal 0.112 all the way to the convincing 0.840 shown above stressing the important of the reduced model. To test homogeneity of variance, the results of Levene's test (which can be used due to the existence of n>2 replicates) can be found below in Figure 1.4, along with a versus fit plot and the two main factor plots shown below that in Figure 1.5 [6].

Figure 1.4



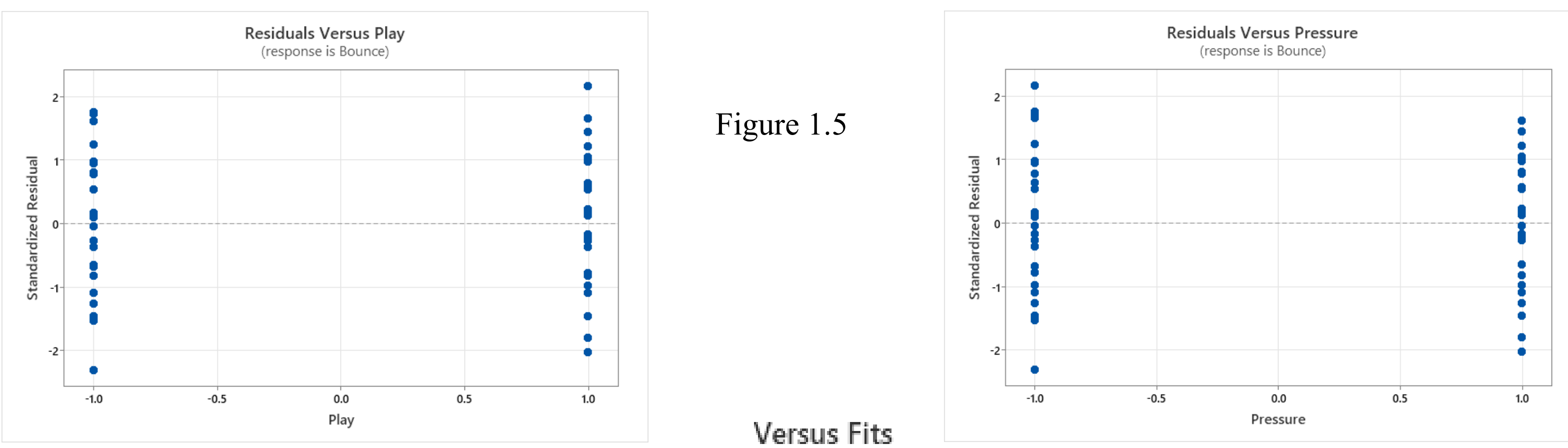
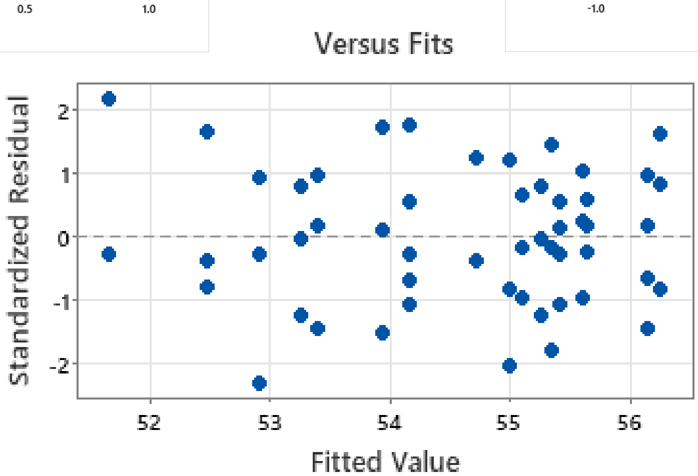
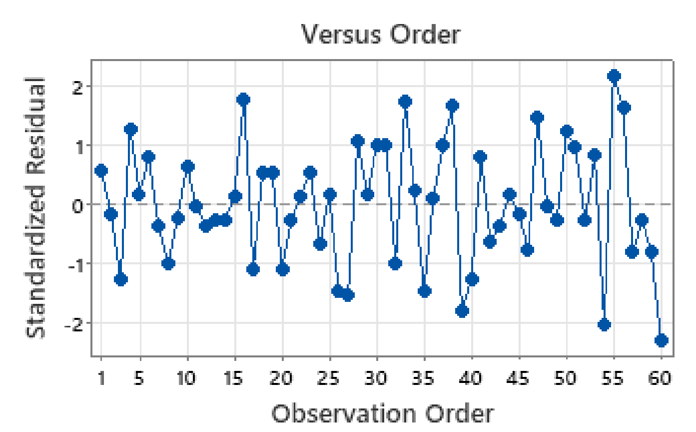




Figure 1.5



The Levene's test p-value in Figure 1.4 confirms that the homogeneity of variance assumption is met[7]. It is also worth nothing how, according to the intervals in Figure 1.4 and Pressure factor plot in Figure 1.5, the variation in Bounce is much lower in the 2 treatments that were kept in pressurized storage containers. There is also no standardized outlier outside the range of (-3,3), so the assumption of no outliers is met as well[7]. The final assumption needing to be met, independence, can be visually tested throw a versus order plot which can be seen below in Figure 1.6[6]. Recall that for each of the 5 testing periods, each of the 12 balls were selected to be measured in a completely random order.

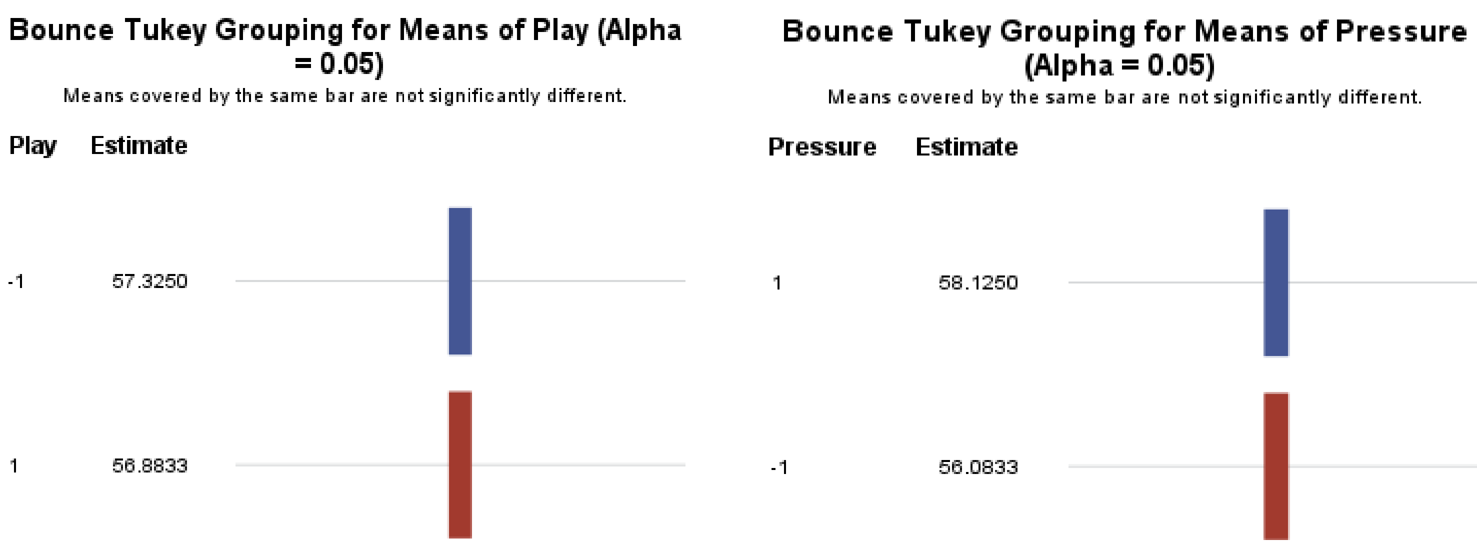
Figure 1.6




It is clear based on the above figure the residual variance is relatively unique throughout the entire run order of 60 runs, therefore the assumption of independence is met[7]. With the residual analysis complete and all four assumption being met, the data can be analyzed without need for transformation and conclusions drawn regarding comparisons of estimated means between the factor levels of the 2 main factors of interest.

Due to the fact that, as shown in the full model back in Figure 1.1, there is not a significant interaction between Play and Pressure, separate Tukey's multiple comparisons tests can be conducted on both factors to determine the difference, if any, in estimated means among their 2 factor levels. The results of those Tukey's multiple comparison test can be seen below in Figure 1.7[6].

Figure 1.7




As shown in the above Figure, there are statistically significant differences in estimated means between levels for both main factors. While it isn't necessarily shocking that using tennis balls every other day for the duration of the experiment results in a lower estimated bounce, the results of the right chart answer the main question being asked in this experiment and show that keeping tennis balls stored in pressurized containers do in fact result in a higher estimate bounce height compared to tennis balls stored in normal, already-opened, non-pressurized, plastic canisters. Diving even deeper into the analysis, a Root MSE of 0.721 means that the difference between the high and low estimate factor levels for Pressure are 2.83 sigmas apart signifying an extremely high confidence level that these results are accurate and that tennis balls kept in pressurized storage containers do in fact have a higher estimated mean bounce than those that aren't stored in such containers. However, the difference between the high and low estimate factor levels for Play are only 0.61 sigmas apart signifying low confidence that these results are statistically accurate which raises some concern as to whether or not playing with tennis balls makes any difference at all when taking into account container pressurization.

Overall, this experiment proved very useful in identifying the effects that both usage and storage method of tennis balls have on balls' respective bounce height. Both main factors, Play and Pressure, were deemed statistically significant in terms of their impact on the response variable, height. However, the results of this experiment have shown that, with a very high level of confidence, storage method of tennis balls is much more significant than whether or not the balls are used regarding optimization of bounce height. Furthermore, keeping tennis balls stored in a pressurized container results in, at a statistically significant level, higher bounce height on average for a longer duration of time.

# Appendix A: Experimental Good Practice Reference Numbers

Practice #1 – Factor and Level Selection

Practice #2 – Randomization

Practice #3 – Replication

Practice #4 – Blocking

Practice #5 – Evaluate Measurement System & Record All the Data

Practice #6 – Plots

Practice #7 – Residual Analysis

Practice #8 – Pool Non-Significant Interactions