An analysis of the relationship between front leg force exertion and velocity in pitchers

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Introduction

An old adage in baseball, from little league fields to the big leagues, is to have a strong "backside." The always alluded to "backside," refers to the back leg of the pitcher and his ability to push off of the mound. However, it is common that a pitcher does not have his back leg planted in the ground when throwing and his back foot and leg are completely in the air at the point of ball release (see below). While the back leg in a pitcher is certainly important in pushing off of the mound initially, it appears to play no role at the point of release as the entire weight of the body is on the front leg.

The aim of this paper is to determine whether force exerted into the ground by the front leg can be a determining factor in the exit velocity of a thrown baseball and to improve upon the statistical methods used for analysis. Based on current research done on the subject, we theorize that there will be a positive relationship between the front leg force exerted into the ground by the thrower and the exit velocity of the ball.

Current Literature

Current research into the relationship between front leg force and the exit velocity of a thrown baseball is relatively sparse with few robust or significant results. The main body of research stems from the biomechanics lab and baseball specific training center, Driveline Baseball in Kent, Washington. Driveline found that their theory of "good front leg block contributing to velocity," was somewhat supported[1]. Driveline used Neulog and Kistler Force Plates to measure directional force and took a linear regression approach that found insignificant, positive results.

The department of Biomechanical Orthopedics at Johns Hopkins University in Baltimore, Maryland also did a study on foot force in throwing. Their results found that "the lower extremity is an important contributor to the throwing motion.[2]" Their research aimed to quantify the push off of the mound with the back leg in relation to the landing force of the front leg, not the sole landing force of the front foot and leg. The study does not specify whether or not this was done off a mound or on flat ground.

The research team of Escamilla et al. compared front leg force in pitching to a bike rapidly stopping. They write that, "If you collapse the front knee, it's basically an energy leak, some of that momentum and force from your stride gets lost and doesn't get transferred well to your upper half. The more powerfully you drive towards home plate and brace up with your front leg, the more powerfully you will transfer force to your upper half, catapulting over your front leg and accelerating your arm for maximum velocity."[3] Their study used biomechanical sensors placed on the subject's body to analyze the body.[4]

A study done out of Bowling Green State University in Bowling Green, Ohio, reaffirms the need for strong legs in throwing. They assert that their data "indicates a high demand for lower extremity strength and endurance" and that "coaches should incorporate unilateral and bilateral lower extremity exercises for strength improvement or maintenance and to facilitate dynamic stabilization of the lower extremities during the pitching motion."[5]

In javelin, the results are consistent with other research done in baseball throwing. In a study done at the University of Chichester in the United Kingdom with 5 javelin throwers, there was a higher force, measured in bodyweights (BWs) put into the ground through the front leg than the back leg during a throw (192 ±64 BWs vs 115 ±35 BWs).[6]

The overwhelming consensus in the baseball community is that strong legs are essential to throwing a baseball with high velocity. However, what the community at large does not know is whether strong legs lead to increased velocity by exerting a large amount of force into the ground or whether having strong legs provides for a better axis to rotate on. We aim to clarify the former of the two.

Experiment Setup and Data Summary

Our experiment was done at Macalester College in St. Paul, Minnesota in collaboration with Macalester College pitchers and their pitching coach, Casey Jacobson. We used Neulog Force Plates in order to measure and record the peak front foot and leg force imparted into the ground by the pitchers throughout their throwing motion in a "rocker drill." The experiment used players and pitchers from Macalester College as well as a former professional pitcher. After warming up, players threw from a "rocker drill" with their front foot placed on a Neulog Force Plate. The Neulog Force Plate was placed on a rubber mat on grass with a net approximately 15 feet away for each participant to throw into. For each pitch, we recorded the ball velocity in miles per hour and the peak force in Newtons. With these results, we calculated force per pound.

```
FFF <- read.csv("FFFXV.csv")
FFF$ForcePerlb <- FFF$Force/FFF$Weight
summary(FFF)
```

```
##     Velocity         Force          Weight        ForcePerlb
##  Min.   :62.80   Min.   : 790   Min.   :178.0   Min.   :3.591
##  1st Qu.:68.90   1st Qu.:1080   1st Qu.:185.0   1st Qu.:5.386
##  Median :71.70   Median :1163   Median :195.0   Median :6.068
##  Mean   :71.43   Mean   :1189   Mean   :196.3   Mean   :6.071
##  3rd Qu.:74.15   3rd Qu.:1262   3rd Qu.:200.0   3rd Qu.:6.581
##  Max.   :79.80   Max.   :1590   Max.   :220.0   Max.   :7.950
```

Variable	Min	Max	Mean
Velocity	62.80	79.80	71.43
Force	790.00	1590.00	1189.00
Weight	178.00	220.00	196.30
Force Per lb	3.59	7.95	6.07

Bayesian Regression

```r
# Import rjags
library(rjags)
```

```
## Loading required package: coda
```

```
## Linked to JAGS 4.1.0
```

```
## Loaded modules: basemod,bugs
```

Our Bayesian regression incorporates two variables that affect velocity: force and weight. We are most intersted in the relationship between force and velocity, but must include weight here as a control. Otherwise, we risk a bias in our regression where increased weight may correlate with increased force and thus the relationship we observe between force and velocity becomes clouded with the relationship between weight and velocity. So in our regression, we use force/weight. In other words, we hypothesize that two individuals of the same weight will throw with different velocities if one is able to impart more force per pound of body weight into their front, landing leg

Our variables are defined as follows:

$$Y = Velocity$$
$$X = Force/Weight$$

Our overall relationship, then, is represented as:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

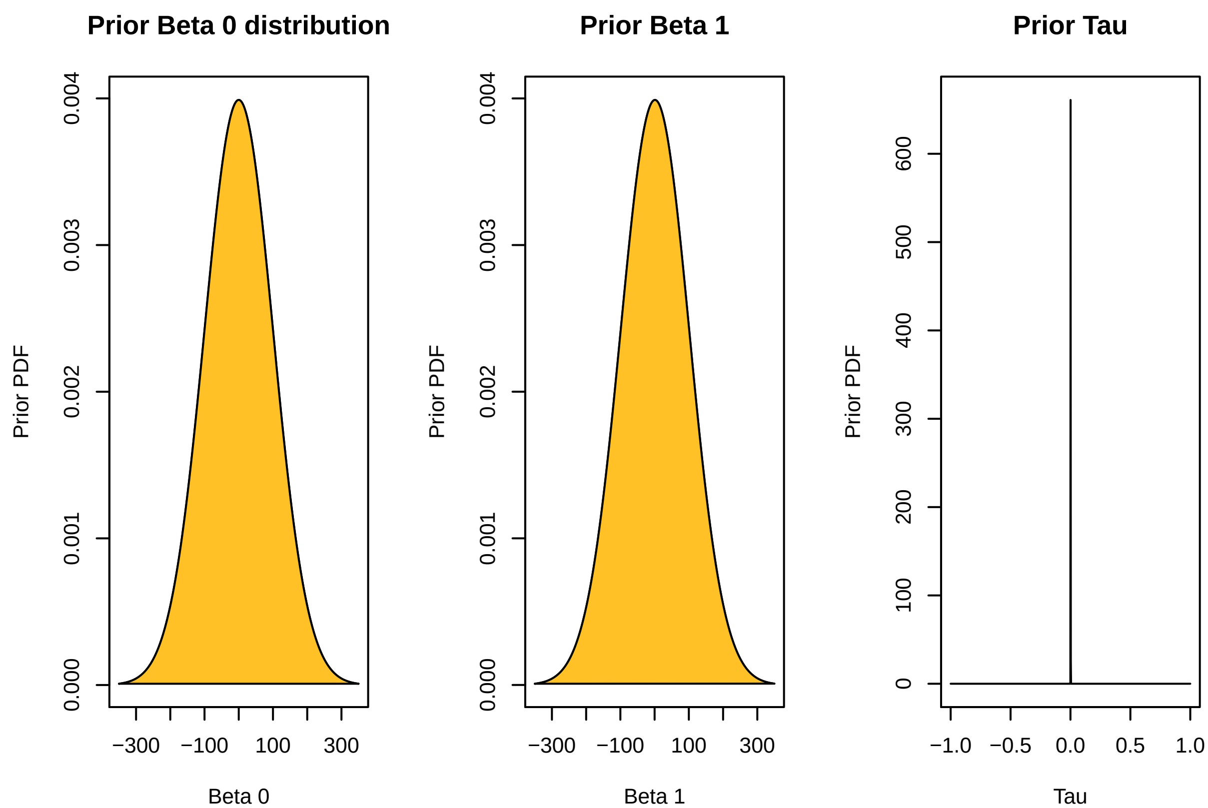
Prior Distribution

Traditional linear regression allows only for the analysis of collected data in a single experiment. Taking a Bayesian approach allows us to improve the robustness of this exercise by incorporating results from other studies in this field alongside the data we have collected in our experiment.

We begin by setting priors on β_0, the intercept velocity, β_1, the relationship between front leg force per pound and velocity, and τ, the inverse standard deviation used to determine ϵ, the measure of random error. We base our priors on previous research that suggests a positive correlation between increased front leg force measurement per pound and increased velocity. There is no reason to believe that any of the regression variables are anything other than normally distributed around some mean, μ, with some standard deviation, σ, so we use the normal distribution as our a priori distribution. We will take a vague approach, specifying a large standard deviation, to our priors to leave room for the possiblity that previous research is not totally accurate. We will assume the random regression error is typically around 0, as is common in statistical analysis.

$$Y_i|\beta_0, \beta_1, \tau \overset{ind}{\sim} N(\beta_0 + \beta_1 X_i,\ \tau^{-1})$$
$$\beta_0 \sim N(0, 100)$$
$$\beta_1 \sim N(1, 100)$$
$$\epsilon \overset{ind}{\sim} N\left(0, \tau^{-1}\right)$$
$$\tau \sim Gamma\,(3, 2700)$$

```r
# Prior plots
par(mfrow = c(1,3))
x   <- seq(-350,350,length=1000)
y   <- dnorm(x,mean=0, sd=100)
plot(x,y, type="l", lwd=1, xlab = "Beta 0", ylab = "Prior PDF",
     main = "Prior Beta 0 distribution")
polygon(x,y,col='goldenrod1')

x2   <- seq(-350,350,length=1000)
y2  <- dnorm(x2,mean=1, sd=100)
plot(x2,y2, type="l", lwd=1, xlab = "Beta 1", ylab =
       "Prior PDF", main = "Prior Beta 1")
polygon(x2,y2,col='goldenrod1')

x3 <- seq(-1,1, length = 1000)
y3 <- dgamma(x3, 3, 2700)
plot(x3, y3, type = "l", lwd = 1, xlab = "Tau", ylab =
       "Prior PDF", main = "Prior Tau")
```



Our prior distribution beliefs indicate a vague, 1:1 relationship between front leg force per pound and velocity. In other words, a priori we allow for high variance in the regression variables, β_0 and β_1, but predict an "average equation" of $Y = 0 + 1X$.

Results

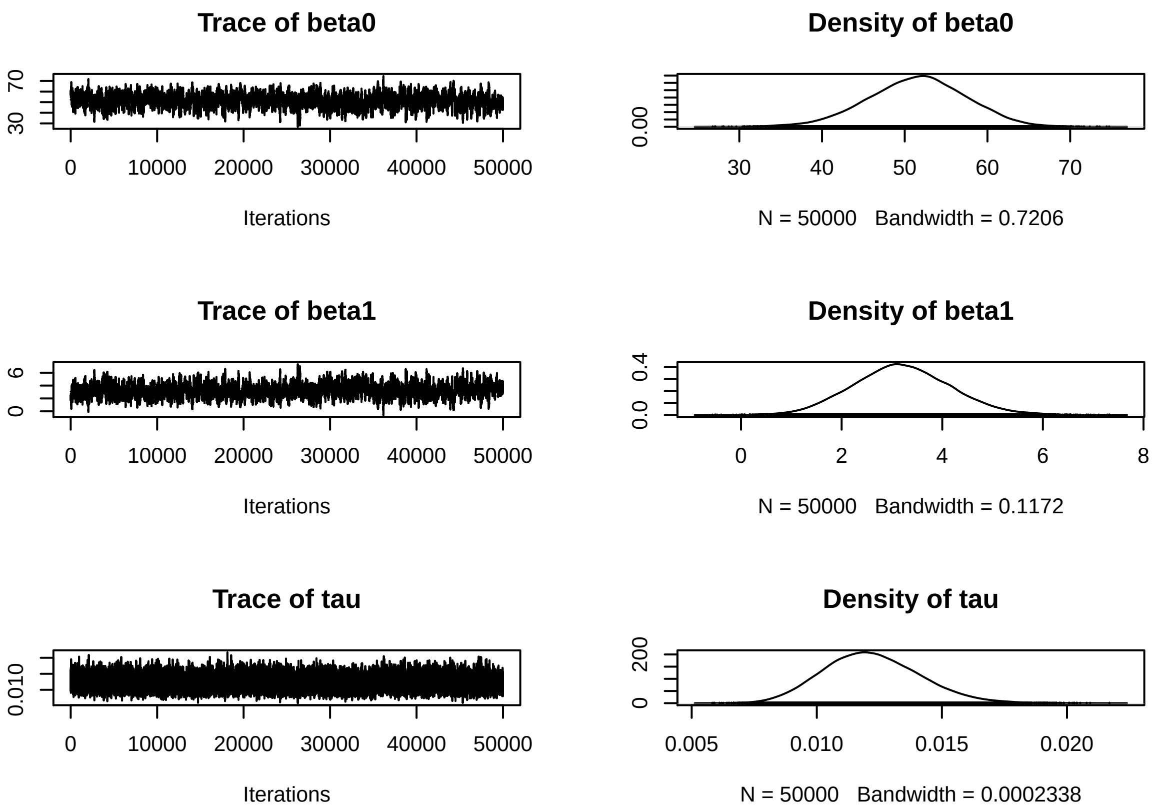
Given our priors, we now use the rjags software package to create a model that combines 50,000 simulated iterations of the experiment under the prior beliefs and our observed data.

```r
#specify the model
FFFModel = "model{
  #Data
  for(i in 1:length(y)) {
    #Note: dnorm in rjags takes the precision, not st. dev.
    y[i] ~ dnorm(mu[i], tau)
    mu[i] <- beta0 + beta1*x[i]
  }
  #Priors
  beta0 ~ dnorm(0,1/100)
  beta1 ~ dnorm(1,1/100)
  tau ~ dgamma(3, 2700)
}"

#construct posterior: combine the model (FFFModel) and data (FFF)
#set the random number seed
FFFJAGS = jags.model(textConnection(FFFModel),
    data = list(y=FFF$Velocity, x=FFF$ForcePerlb),
    inits=list(.RNG.name="base::Wichmann-Hill", .RNG.seed=1989))
```

```
## Compiling model graph
##    Resolving undeclared variables
##    Allocating nodes
## Graph information:
##    Observed stochastic nodes: 91
##    Unobserved stochastic nodes: 3
##    Total graph size: 368
##
## Initializing model
```

```r
#simulate a sample from the posterior
FFFSample = coda.samples(FFFJAGS,
    variable.names=c("beta0","beta1","tau"), n.iter=50000)

#store the samples in a data frame:
FFFSampData <- data.frame(FFFSample[[1]])
```

```r
plot(FFFSample)
```




```r
summary(FFFSample)
```

```
##
## Iterations = 1:50000
## Thinning interval = 1
## Number of chains = 1
## Sample size per chain = 50000
##
## 1. Empirical mean and standard deviation for each variable,
##    plus standard error of the mean:
##
##          Mean      SD  Naive SE Time-series SE
## beta0 51.5154 5.93175 2.653e-02      2.306e-01
## beta1  3.2022 0.96767 4.328e-03      3.767e-02
## tau    0.0122 0.00192 8.585e-06      3.051e-05
##
## 2. Quantiles for each variable:
##
##            2.5%      25%     50%      75%    97.5%
## beta0 39.512738 47.61015 51.6586 55.54011 62.79813
## beta1  1.371161  2.54784  3.1796  3.83724  5.16080
## tau    0.008734  0.01085  0.0121  0.01345  0.01622
```

Method	$\hat{\beta}_0$	95% CI for β_0	$\hat{\beta}_1$	95% CI for β_1
prior	0		1	
posterior	52.950	[40.095, 62.793]	3.132	[1.380, 5.062]

The mean result in our model gives a regression equation of:

$$Y = 52.950 + 3.132X$$

This indicates a positive relationship between front leg force per pound and increased velocity. The value to note is 3.132, or the slope of the relationship between X, the front leg force per pound in Newtons and velocity. If a pitcher is able to impart one more Newton of front leg force into the ground per pound of weight, our study predicts an increase in velocity by 3.132 MPH. As an example, for a pitcher who weighs 180 pounds if he is able to increase his per pound force by one Newton, or 540 Newtons overall, we would expect a 3.132 MPH increase in a thrown pitch. The 95% confidence interval is relatively small and, most importantly, entirely positive. Thus, our model provides a confident, positive relationship result.

Concluding Remarks

This project seeks to improve the small amount of existing research literature on the relationship between front leg force and velocity in a throwing motion by performing further experiments and by improving on the statistical methods generally used to study results. Our results use a Bayesian regression method that finds a positive relationship between front leg force per pound and velocity. We would expect a 3.132 MPH increase in velocity for every one Newton per pound increase in front leg force exertion.

We theorize that this relationship is seen because front leg force can be a proxy for stored energy in the throwing kinetic chain. If a pitcher is able to create a large amount of forward moving energy (for example driving hard off the back leg) when he lands with his front leg as a brace, he will produce great downard force. Efficiently translating this energy into rotational energy as he rotates his trunk before releasing the ball will result in a high velocity. Due to the nature of the pitching chain of movements, ideal variables that could be used for controls in future studies would be arm velocity, directional force of the landing leg, and the speed and force of the trunk rotation. Being able to control for whip in the upper body would help isolate the effect of front leg force and avoid a situation where a player may impart higher force in his front leg but cannot effectively use his upper body to convert the energy into velocity.

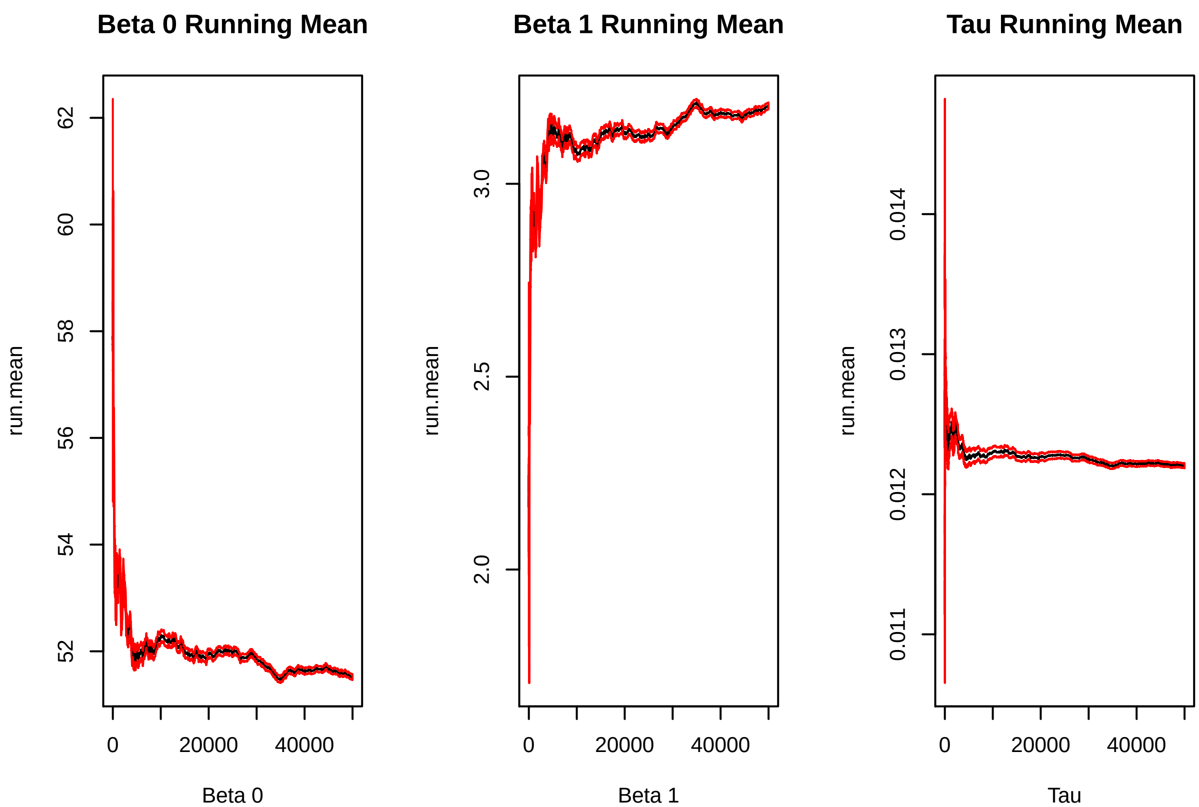
Appendix

The following plots are included to show that the chosen number of iterations, 50,000, sufficiently converges to a result that is robust against random sampling error.

```r
# This function provides a running mean plot for a given variable
running.plot = function(x,bars=FALSE,...){
 n = length(x)

 #Calculate the running mean of x:
 run.mean = cumsum(x)/c(1:n)

 #Calculate the running margin of error
 moe.run = rep(0,n-1)
 for(i in 2:(n-1)){
  moe.run[i-1] = 1.96*sd(x[1:i])/sqrt(i)
 }

 if(bars=="FALSE"){
  #Plot the running mean versus sample size:
  plot(c(1:n), run.mean, type="l", ...)
 }
```

```
  if(bars=="TRUE"){
  #Plot the running mean versus sample size:
  plot(c(1:n), run.mean, type="l", ylim=c(min(run.mean[-1]-moe.run),max(run.mean[-1]+moe.run)), ...)
  lines(c(2:n), run.mean[-1] + moe.run, col=2)
  lines(c(2:n), run.mean[-1] - moe.run, col=2)
 }
}
```

```
par(mfrow = c(1,3))
running.plot(FFFSampData$beta0, bars = TRUE, xlab =
               "Beta 0", main = "Beta 0 Running Mean")
running.plot(FFFSampData$beta1, bars = TRUE, xlab =
               "Beta 1", main = "Beta 1 Running Mean")
running.plot(FFFSampData$tau, bars = TRUE, xlab =
               "Tau", main = "Tau Running Mean")
```



In these running mean plots, the black line indicates the mean of all iterations up to iteration x_i and the red lines indicate the 95% confidence bounds. These plots show that after 50,000 iterations the mean of the existing iterations converges and stabilizes around a small range of possible values. After 50,000 samples, the mean we present is confidently free of random sampling error.

Acknowledgements

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References

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