Down Weight versus Equation Piano Key Balancing: Shifting the Paradigm

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Abstract

Traditional down weight piano key balancing is shown to limit factory production quality. It also contributes to degradation of the piano over time due to a lack of guidelines for aftermarket refinement and parts replacement. Equation key balancing is shown to improve factory production quality and provide clear guidelines for aftermarket refinement and parts replacement. Most importantly it includes the addition of hammer weight balancing to the traditional set of skills.

Introduction

Setting weights into piano keys for making a specified down weight to create a smooth and predictable response across the keyboard has always been, and will always be, a goal in piano making. Down weight key balancing has been the status quo over the long and colorful 300 year history of the piano. New knowledge is shifting the paradigm.

The discovery of the Equation of Balance[1] in the 1990's shed new light on our understanding of the key balancing. A simple algebraic expression tied together seemingly complex relationships between multiple piano touch weight components that all effect the way a piano feels and responds when played. These components include hammer and hammer shank weights, key balancing weights, action ratios, wippen weights, friction weights, and balance weights as well as up weights and down weights. The fundamental relationships defined by the equation had remained unquantified up until that time. The likely explanation is that the development of piano key balancing had evolved empirically. The down weight method worked well enough through the ages in the factory production environment.

In the last decade of the 20th century the business of restoring vintage high quality pianos emerged as major market for small shops and rebuilding companies. This renaissance was fueled by favorable economic conditions and a large pool of fine pianos made over the preceding 100 years to draw from, combined with an explosion of knowledge regarding restoration techniques that was made available by the Internet.

When a piano goes through a major overhaul with new parts the keys have to be balanced. The traditional down weight method proved to be quirky. Some times it would give good results but more often not. As a result the rebuilding a piano had long been considered risky because the outcome of how it would play was always uncertain. All these factors provided strong incentive to come up with a more comprehensive method of balancing pianos and the equation of balance was born out of that need.

The new technologies spawned by the equation of balance simply allow for smarter more reliable ways of doing things that have long been done, and will always be done, in the construction of pianos. The exception is hammer weight balancing. This is a new skill set for the trade. Interest and enthusiasm for the advantages gained from hammer weight balancing is steadily growing and gaining acceptance here in North America, in Europe, and most notably in Germany.

These methods have proven to be a boon for the rebuilding and restoration business as well as for the business of customizing and upgrading fine pianos for demanding clients with special needs and desires. How can they be integrated with long held traditions and applied practically to factory production of new pianos? What are the benefits and challenges?

Materials and Methods

Touch weight component measurements were taken on a high end concert prepped grand piano, factory balanced with the traditional down weight weigh off. A standard 4 panel analysis graph series was produced from the data. The data was then manipulated using the equation of balance to simulate the effects of smoothing friction weights and hammer weights as well as with replacement of hammers - such as might be done by piano technicians in the aftermarket**.** A graph set of idealized equation derived touch weight component specifications was created. Then a graph series was generated to simulate how touch weight would look with equation balanced keys combined with unrefined hammer weights and friction weights. Aftermarket friction weight smoothing, hammer weight smoothing, and ratio smoothing was then simulated for the equation balanced action. The resulting graphs series illustrate the differences produced and issues raised from the application of both key balancing methods.

Measurements and calculations for these virtual scenarios were made according to *Standard Protocols of the New Touch Weight Metrology* with calculations based on the Equation of Balance, as published in the Piano Technicians Journal February 2000. Formulas used for data series calculations are given in Appendix A

Results and Analysis

Figure 1. – Down weight balanced as from the factory

Strike Weight is a measure of hammer weight made by tipping a shank mounted hammer onto a digital scale. Standard low, medium, and high zones[2] are shown by the solid arching lines. Note the jump of 0.8 grams between notes 42 and 43 and the elevated weights between notes 43 and 65. This is due to the hammer molding wood being denser in that section. Pianists can easily feel a 0.5 hammer weight change so this is a significant anomaly. Strike weight studies performed over the last 20 years show that variations of 1.0 grams between adjacent notes is common. Studies also show that strike weight levels between like sets of the same make/model/period commonly span a range of as much as 2.0 grams.

The Touch weight graph shows a good vestige of the original factory made down weights with a number of sections that are still smooth and even. Up weights are less smooth that the down weight because friction weights were uneven when the keys were balanced. The balance weights are also uneven as a result of uneven friction weights as well. Medium and Low Friction weight zones[3] are delineated by straight solid lines on the graph. Friction Weights are mostly in the low zone.

The strike weight ratio graph shows scattered calculated values with an average of 6.0 which is in the middle of the medium zone[4]. Studies show that this scattering is normal even for high quality pianos. Some of the variations are traceable to inaccurate positioning of leverage points within each key such as capstan position, balance rail position, and knuckle placement and/or misinterpretation of down weight and up weight measurement during the analysis. Furthermore studies show that ratio values change as the action wears or if parts are replaced. Studies show that a change in level of 0.3 ratio creates a significant change in the feel of the action.

The Front Weight graph shows the effect of the factory installed key weights. The Front Weight measure is taken by tipping each keystick on it's balance point and resting the front of the key onto a digital scale. Low, medium, and high zones are shown by the solid arching lines. The line between the high and medium zone is the "Front Weight Ceiling" [5]. The inconsistent front weight values are the result of uneven strike weights, friction weights, and ratio values that existed at the time of the weigh off in the factory. Studies show that front weight values for key weighting patterns vary widely within like makes and models of pianos.

Figure 2. Down weight balanced with smoothed friction weights

With aftermarket fine tuning of friction weights, down weights and up weights become less smooth.

Figure 3. - Down weight balanced with smooth friction weights and strike weights.

When strike weights are smoothed, further degradation to the down weights and up weights occurs.

Fig. 4 - Factory front weights with replacement hammers.

When worn out hammers are replaced with a new of replacement hammers, there is a high probability that the weights of the replacement hammers will not be similar those originally used. This can wildly throw off the down weights and up weights.

Figure 5 - Equation Key Balancing Specifications

This is a set of equation balancing specifications showing an idealized representation of the original factory component touch weight analysis of figure 1.

Figure 6. - Equation balanced front weights

When keys are balanced to front weight specifications only. Down weights and up weights are rough. This is the result of the combined variations in friction weights, ratios, and strike weights.

Figure 7. Equation balanced front weights with smoothed friction weights

With aftermarket fine tuning of friction weights, down weights and up weights become less chaotic.

Figure 8. Equation balanced front weights with smooth friction weights and strike weights

Balancing the hammer weights to make smooth strike weights yields a significant smoothing of down weight and up weight. When front weight and strike weights are equation balanced, the balance weights become indicators of ratio. Note that the pattern of balance weights matches the pattern of the strike weight ratios.

Figure 9 - Equation balanced front weights with smooth friction weights, hammer weights, and ratios.

Modifying key bearing points and/or fixing other out of place pivot points such as capstans or knuckles, realizes a very close approximation to the idealized equation derived touch weight component specifications.

To summarize the results: With down weight balancing, the piano starts out with smooth down weights. As friction weights and strike weights are smoothed, down weights and up weights become rougher. All bets are off with replacement hammers.

With equation balanced keys the piano starts out with smooth key weighting and friction weights, strike weights, and ratios are rough. As the roughness of these components are smoothed out, down weights and up weights become smoother.

Discussion

Pianists want and expect a predictable response from each key that gives them a feeling of connection with the tone, as well as playing force that is not too low or high. Traditional down weight key balancing is intended to support these needs.

The results of virtual key balancing scenarios teach us that there are problems with addressing these needs using the traditional down weight method. It limits piano quality and set's a path for degradation of that quality as the piano ages. We see that smooth factory down weights mask inconsistencies of touch weight components. Smooth down weights are "locked in" to the key weighting from each particular set of inconsistencies. Furthermore each unique set of inconsistent touch weight components may or may not be even close to ideal, and these sets are randomly different for every piano, even those of the same make/model/period.

An inconvenient truth about down weight key balancing is that anytime friction weights and hammer weights change, or action parts wear and are changed, the meaning of the key weighting is lost, requiring successive rebalancing of the keys in order to maintain factory down weights. This puts the responsibility for maintaining the integrity of balance and the resulting quality of the instrument upon piano technicians in the field, with little in the way of guide lines besides a down weight specification. This can and does lead to disastrous results. Fig. 10. shows a worst case example of a piano key from a high quality vintage piano that has gone through successive key balancings over its long life.

Another inconvenient truth is that down weight is not a good indicator of the dynamic force that the pianist uses when playing. Down weight, the minimum force needed to move the keys, is usually close to 50 grams. It is measured without the key going through let off, therefore no tone is ever elicited when a pianist plays a piano key with the force of down weight. The speed of down weight is just too slow for the hammer to reach the string and make music. At playing speeds, the laws of inertia apply and the playing forces are much higher than, and not proportional to down weight. Ortmann[6] teaches, as a rough approximation, that the minimal force which a pianist must exert through the stroke of the key to play the softest pianissimo *pp* tone is = 80 grams; *p* = 130 grams; *mp* = 170 grams; *mf* = 280 grams; *f* = 480 grams and higher; *ff* = 900 grams and higher. These values are much higher for pianos that have an intrinsically heavy action. We see that the down weight value most closely relates only to the softest of dynamics and is lost in the shuffle at higher volumes. Engineers report[7] that the 70% - 80% or more of the force that the pianist exerts to move the keys when playing the piano goes into catapulting the weight of the hammer. These dynamic playing forces do not show up in the down weight measurements. A piano can have a low down weight and feel dynamically heavy and vise versa.

These facts call into question the whole meaning of down weight as the primary specification for determining how a piano feels when played. Simply setting the down weight to 50 grams by putting lead balancing weights in the keys does not guarantee much at all about how the piano will react to the touch of the pianist during playing. Furthermore, down weight itself is inconveniently a very unreliable quantity. It is the most subjective and least repeatable of all touch weight measurements. It requires a very specific rapping on the bench to start the hammer moving. The kind of rapping needed varies depending on the solidness of the work bench and judgment of the motion of the hammer is prone to misinterpretation. Up weight is also prone to errors in judging the motion of the hammer during measurement. These truths shift our attention away from down weight and towards what is proven to be the most dominant of touch weight components which is hammer weight. It is evident the importance of hammer weight has somehow become overlooked in the evolution of the piano.

Equation key balancing conveniently addresses these core issues. Down weight exists as a specification but shares the stage with up weight, balance weight, friction weight, key weight, wippen weight, action ratio, and, most importantly, hammer weight. Ideally designed specifications are created for each of these components for every note on the piano according to the equation of balance. Equation key balancing treats touch weight components as parts of a beautiful machine that logically fit together. Reasonable tolerances are applied to the specifications for those parts as the piano is constructed on the factory floor. There are a number of distinct advantages to designing and building pianos with equation balancing:

The long standing problem of friction skewing the key weighting in the factory disappears. Friction can be treated separately and fixed or refined at any time without negative effects on the physical construction of the piano.

Factory key weighting and front weight patterns could be made using minimal skill to a much higher degree of evenness than was attainable even with the highest skill and effort using traditional down weight method. Standardized ideal weight patterns can be adopted.

Having a specification and tolerance for each touch weight component keeps the quality of piano construction on a logical track for the long life of the piano. Aftermarket refinement can take place in context to the design intentions of the piano maker using clear guide lines and specifications. Customizing hammer weight levels accommodates personal client taste for heavier , medium, or lighter action.

Piano factories can easily mass produce pianos with equation balanced key weights and unrefined of hammer weights and touch weight components with little or know additional costs. Makers of high end pianos can produce pianos with equation balanced keys, balanced hammer weights, and refined touch weight components for the highest as-from-factory standard.

Guide lines for equation balanced pianos could include:

1. A notice that key weights are set in the factory and are never need to be changed. When action parts are replaced they need to match the original dimensional factory specifications in order to maintain the integrity of balance.

2. Strike Weight specifications with an associated estimated hammer weight specifications for factory installed or replacement hammers. The strike weight specifications could have three levels to provide light, medium, or heavy dynamic playing quality with associated Balance weight specifications.

3. Balance weight specifications to accompany each strike weight specification level. Balance weight specifications can be used as an analytical tool. If the action is put together to specification the balance weight will be on spec. Balance weight can also be used to track action wear. As the knuckles/rollers wear and get flat balance weight and ratio levels rise, indicating the need for service or replacement.

4. Friction weight specifications for medium or low friction style actions.

Summary

Equation key balancing and the use of touch weight component specifications demonstrates a number of advantages over the traditional down weight method for factory production of pianos. The greatest challenge is the addition of the new skill set of managing hammer weights and strike weights. Piano makers will have to pay more attention to see that hammer weights they use in the factory, or for replacement sets provided to technicians in the field, fall within an acceptable tolerance. Technicians will have to be trained in hammer weight balancing skills. Looking at the results of grass roots experience in the trade from two successful decades of aftermarket hammer weight balancing it is apparent we are ready to face and happily accept this challenge.

Footnotes

1. Stanwood, D **1996.** *The New Touch Weight Metrology* Piano Technicians Journal, June 1996 P. 16

2. Stanwood, D **2000.** *Through the Eyes of The New Touchweight Metrology* Piano Technicians Journal March 2000 P.21

3. Medium and low friction weight zones were created by analyzing the more strict Steinway touch weight specifications that were used during the middle of the 20th century. Down weight and up weight specifications were by section. On average down weight was specified at 50 grams in the bass tapering to 46 grams in the treble. Up weight was 20 grams in the bass tapering to 24 grams in the treble. (Steinway factory specifications provided by William E. Garlick) Calculating friction weights from these yields a friction weight specification of from 15 grams in the bass to 11 grams in the treble. Using this as a bass line for medium friction, a zone of plus or minus 2 grams was delineated making a zone spanning 4 grams. A low zone was delineated as 4 grams lower than the medium zone.

4. Stanwood, D **2000.** *Through the Eyes of The New Touchweight Metrology* Piano Technicians Journal March 2000 P. 24

5. Stanwood, D **2000.** *Through the Eyes of The New Touchweight Metrology* Piano Technicians Journal March 2000 P. 25

6. Ortmann, O. **1925** . *The Physical Basis of Piano Touch and Tone* Kegan Paul, Trench, Trubner; J. Curwen; E. P. Dutton, London. P .41

7. Fandrich, D; Rhodes, J *Inertia - The Invisible Load* Fandrich, D Rhodes, J , Piano Technicians Journal, 2013 July 2013 P. 22

Appendix A

Terms:

SW = Strike Weight
R = Strike Weight Ratio
FW = Front Weight
KR = Key Weight Ratio
WW = Wippen Radius Weight
WBW = Wippen Balance Weight
D = Down Weight
U = Up Weight
BW = Balance Weight
F = Friction Weight

Data and Calculations

WBW value used for all calculations is the average of measured and computed values from Notes: 16,17,40,41,64, & 65 as from the factory

Figure 1 – Down weight balanced as from the factory

SW = as measured
FW = as measured
D = as measured
U = as measured
BW = (D + U)/2
F = (D – U)/2
WBW = KR x WW
R = (BW + FW –WBW) / SW
WBW values used for all calculations is the average of measured and computed values from Notes: 16,17,40,41,64, & 65 as from the factory

Figure 2 - Down weight balanced with smoothed friction weights

BW = as calculated in Fig. 1
F = Linear regression tapering from 13g at note #1 to 9g at note #88 with random variation added to simulate real world friction weight balancing
D = BW + F
U = BW – F
SW = As from Fig. 1
FW = As from Fig. 1
R = As from Fig. 1

Figure 3 - Down weight balanced with smooth friction weights and hammer weights.

SW = as from a curve fitting algorithm that fits to the average of the SW values of Fig.1 with random variations added to simulate real world strike weight balancing
R = as from Fig. 1
FW = as from Fig. 1
WBW = as from Fig. 1
BW = SW x R + WBW – FW
F = As from Fig.2
D = BW + F
U = BW – F

Figure 4 - Front Weights and Strike Weights as from factory with replacement hammer.

SW = as measured with a set of factory replacement hammers
R = as from Fig. 1
FW = as from Fig. 1
WBW = as from Fig. 1
BW = SW x R + WBW – FW
F = As from Fig.2
D = BW + F
U = BW – F

Figure 5 - Equation Key Balancing Specifications

SW = as from Fig. 3 without random variations added
BW = 39 – the average of BW from Fig.1
R = 6.0 – the average of R from Fig. 1
FW = SW X R + WBW - BW
F = as from Fig. 2 without random variations added
D = BW + F
U = BW – F

Figure 6 - Equation balanced without touch weight
component refinement.

SW = as from Fig. 1
R = as from Fig. 1
FW = as from Fig. 5 with random variation added to
simulate real world variation
BW = SW x R + WBW – FW
D = BW + F
U = BW - F

Figure 7 – Equation balanced with smoothed friction weights

SW = as from Fig. 3
R = as from Fig. 1
FW = as from Fig. 6
BW = SW x R + WBW - FW
F = as from Fig. 2
D = BW + F
U = BW - F

Figure 8 - Equation Balanced with smoothed friction weights and strike weights.

SW = as from Fig. 3
R = as from Fig. 1
FW = as from Fig. 6
BW = SW x R + WBW - FW
F = as from Fig. 2
D = BW + F
U = BW – F

Figure 9 – Equation Balanced with smoothed friction weights, strike weights, and ratio

SW = as from Fig. 3
R = as from Fig. with random variation added to simulate
real world ratio smoothing
FW = as from Fig. 6
BW = SW x R + WBW - FW
F = as from Fig. 2
D = BW + F
U = BW – F

Figure 1. – Down weight balanced as from the factory

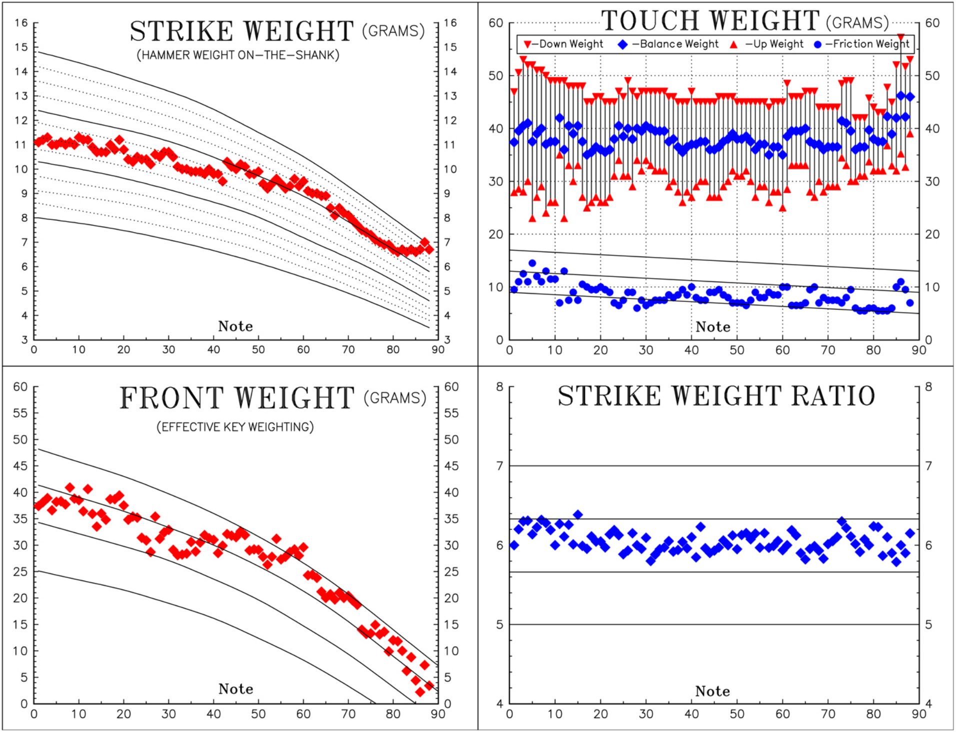

Figure 2. Down weight balanced
with smoothed friction weights

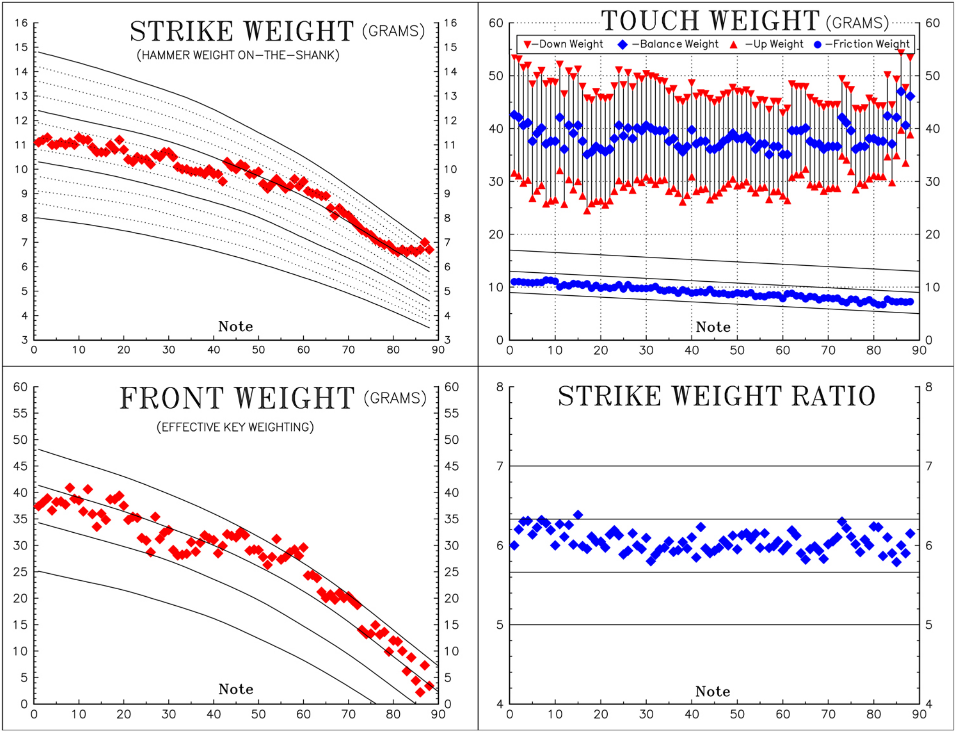

Figure 3. - Down weight balanced
with smooth friction weights and strike weights

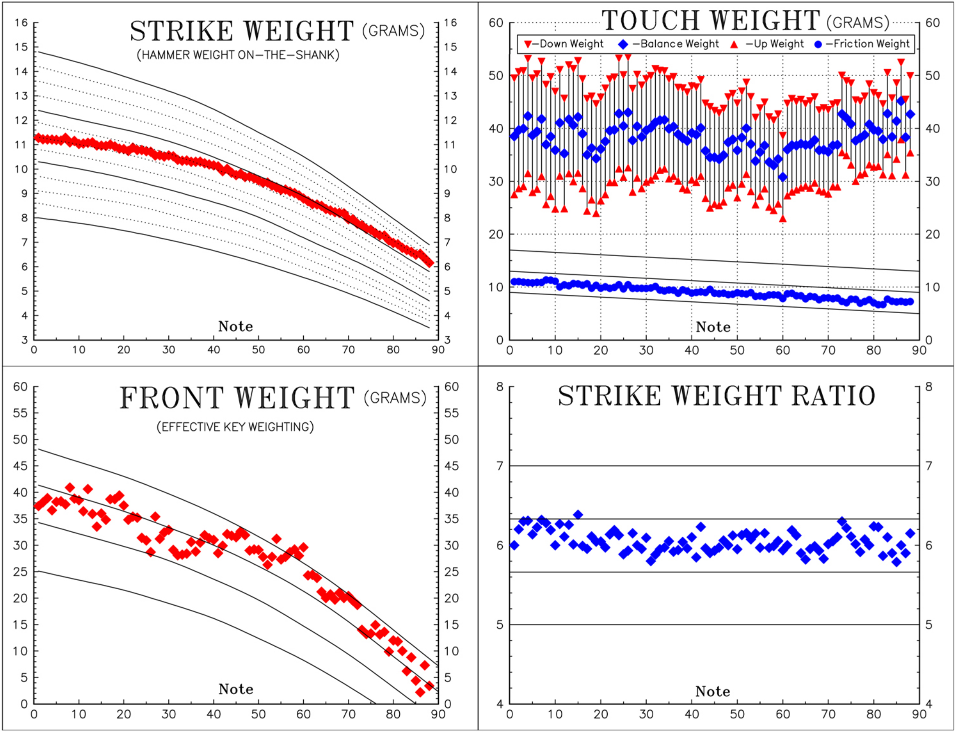

Fig. 4 - Factory front weights with replacement hammers

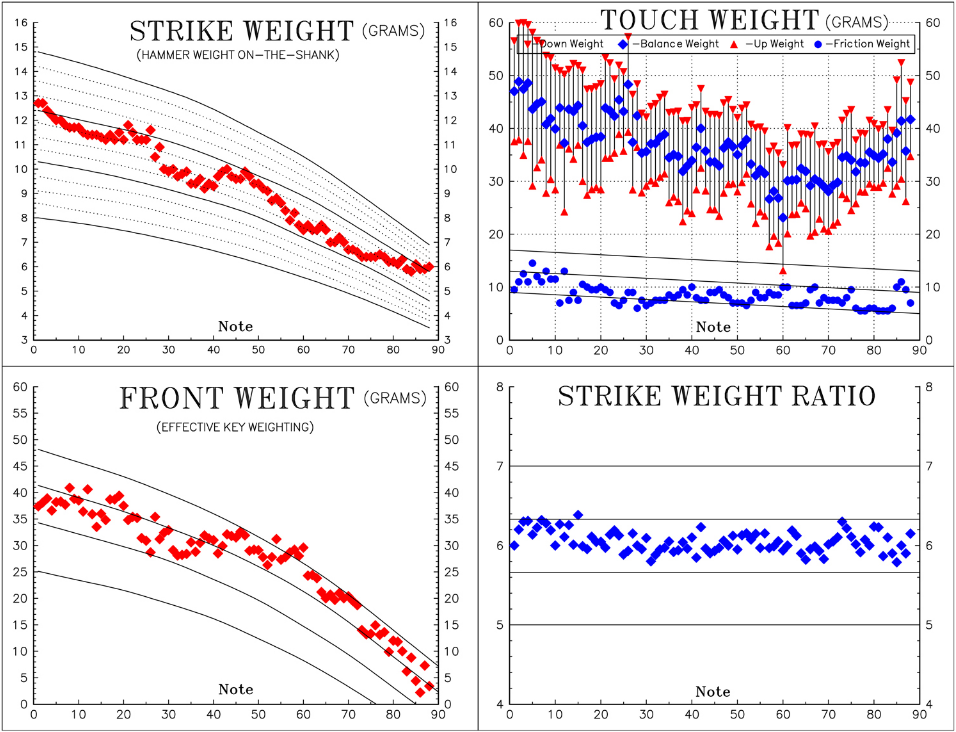

Figure 5 - Equation key balancing specifications

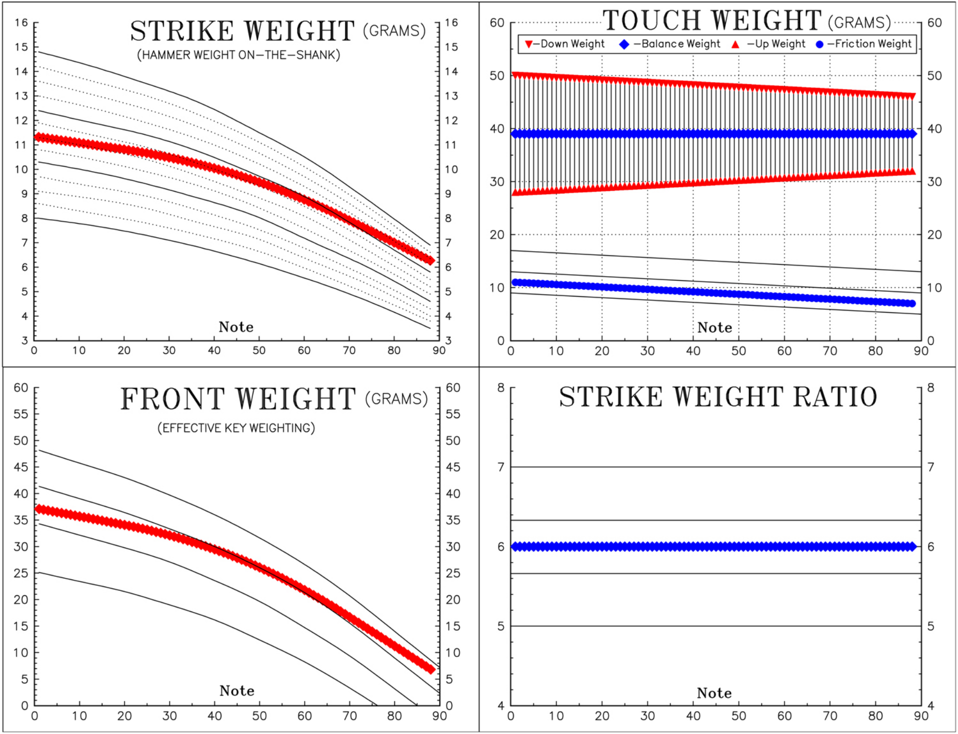

Figure 6. - Equation balanced front weights

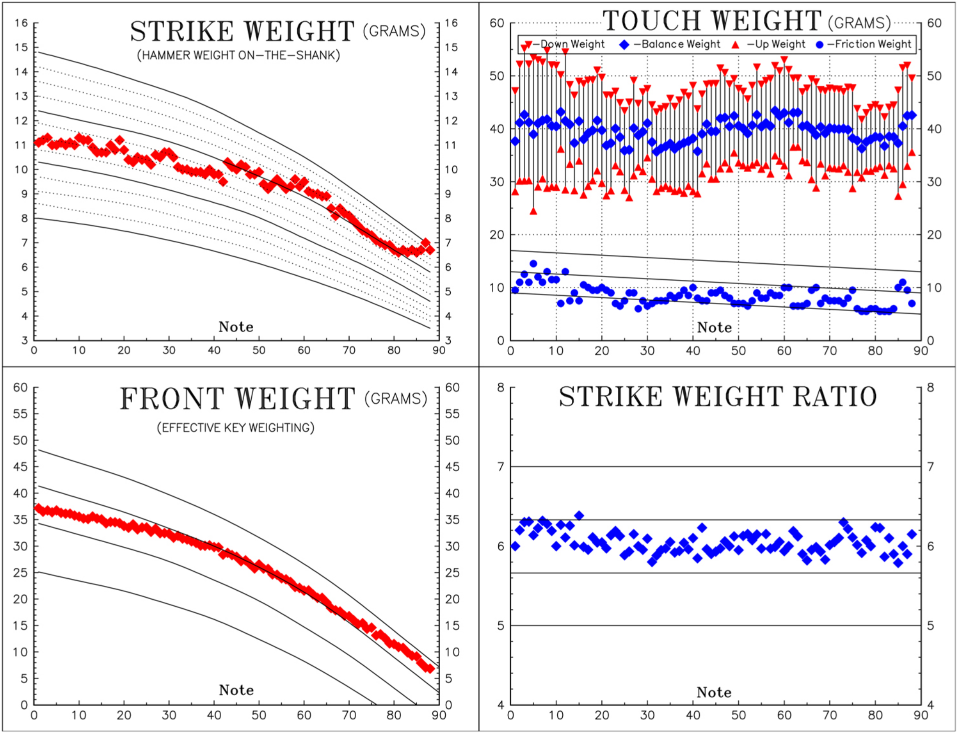

Figure 7. Equation balanced front weights
with smoothed friction weights

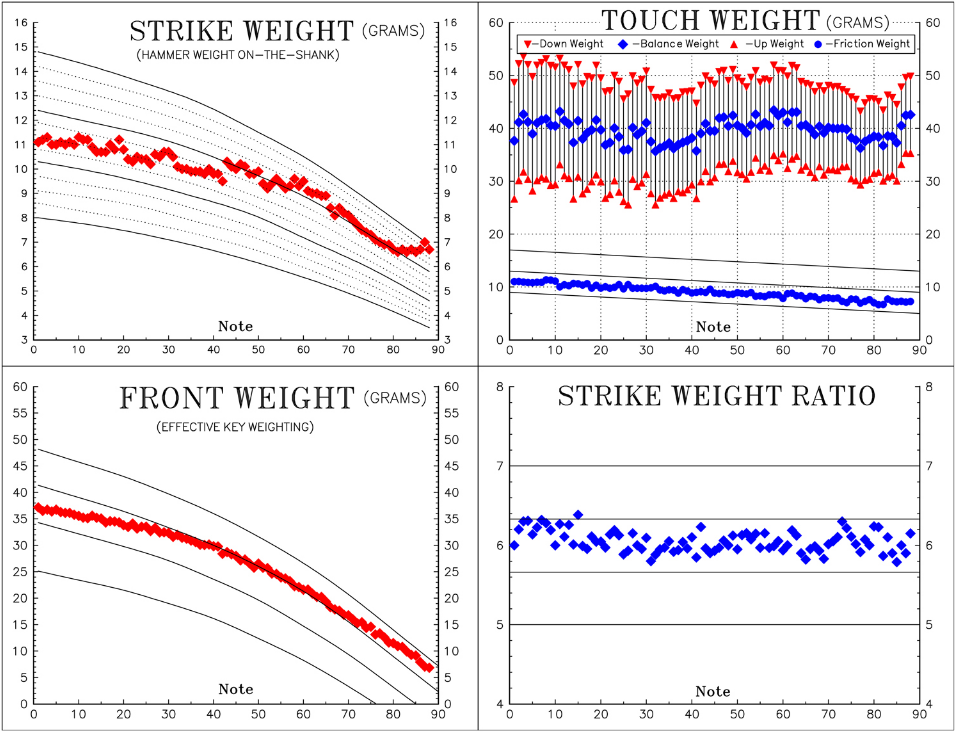

Figure 8. Equation balanced front weights
with smooth friction weights and strike weights

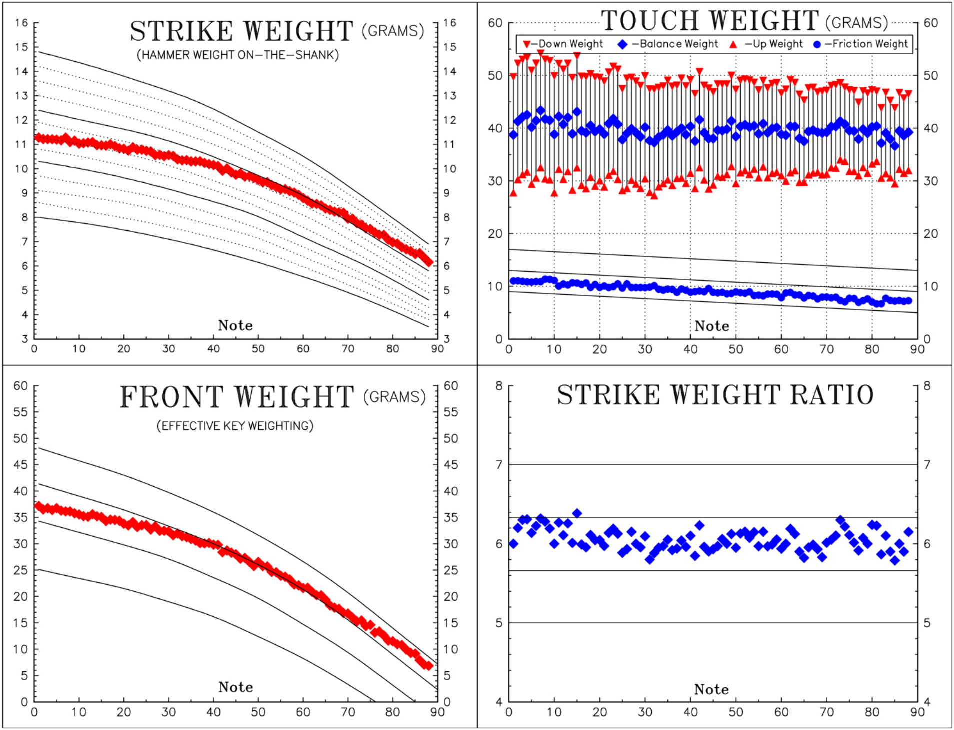

Figure 9 - Equation balanced front weights with smooth friction weights, hammer weights, and ratios.

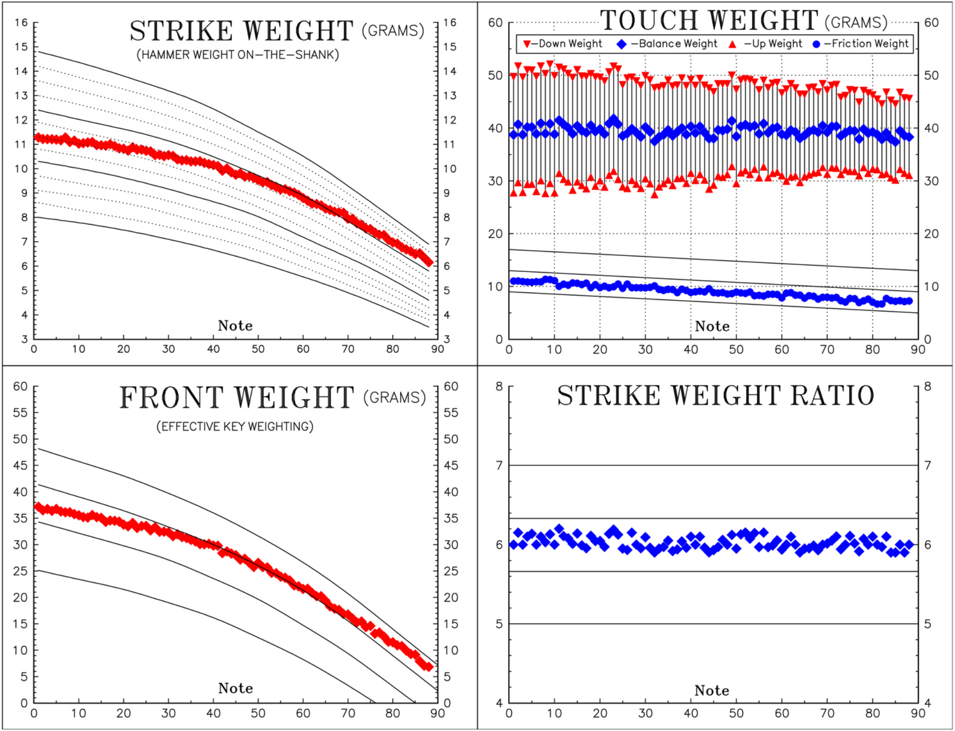

Figure 10. Keys that suffered multiple down weight balancings