Scientific Matching of Golf Clubs

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The author is the inventor of the patented BioMatch method of matching golf clubs within a set and to a user of a particular build. The author is also the founder of Rational Golf LLC incorporated in Florida. Rational Golf LLC is promoting the BioMatch method of matching golf clubs.

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Abstract

Golf club makers have for almost a century matched golf clubs according to various versions of the Swingweight method, which is arbitrary and without any basis in science. This paper discusses the history of attempts to match golf clubs in a set and a recent scientific breakthrough named BioMatch. The BioMatch method matches golf clubs within a set and to a golfer of a particular build. Scientific studies, biomechanics and Newton´s laws of motion form the basis of the BioMatch method. This paper proves that a set of golf clubs cannot be matched for optimum performance without considering the relationship among mass and moment of inertia, and the physical properties of each particular golfer. By scientifically determining the optimal mass and moment of inertia of each club in the set, the upper body, hands, and clubhead will be synchronized so that they all line up at the impact position. This paper proves that a golf club will behave in the same manner as long as the relationship *moment of inertia around the center of the grip/mass of the club* is kept constant. These findings, when applied to any golfer, will improve accuracy and distance.

Keywords: Swingweight, Lorythmic scale, Robert Adams, BioMatch, golf clubs, golf equipment, matching of golf clubs, moment of inertia, MOIG, Rational Golf LLC.

Scientific Matching of Golf Clubs

Matching of golf clubs has been considered the Holy Grail of golf since the beginning of golf club manufacturing about 500 years ago. A properly matched set of clubs will provide superior consistency with regard to the ball flight, direction and distance. Golf enthusiasts have explored a few non-scientific methods over the last hundred years, most notably the *Swingweight* method, still used by the vast majority of golfers today. The golf industry seems to have given up on the search for a scientific method of matching golf clubs. This paper takes a fresh scientific look at the problematic issue of matching and contemplates whether it is even possible to match a set without considering the biomechanical properties of the golfer in question. This new approach creates a dynamic anthropometric model of the golfer in question paired with the relevant set of golf clubs. This approach provides a solution that will serve all golfers by making the game easier to play and thereby more enjoyable, which may aid in recruiting new players to the game. The resulting method is named BioMatch, United States Patent no. 9,022,878, issued on May 5, 2015.

The History of Matching of Golf Clubs

Why Matching Golf Clubs

There are a number of things that can go wrong in a golf swing. If the clubface is half a degree off, the ball can end up 20 meters off target. If the ball is hit 5 mm off the sweet spot, it will have a detrimental effect on distance and direction. The actions and timing of the vast array of muscles involved must be held in the subconscious memory of the golfer (Zumerchik, 2010). One may think of this set of finely tuned actions as a software subroutine. Obtaining the required accuracy with one club, and embedding it in the subconscious mind, is an achievement. To create and memorize a different subroutine for each of the thirteen clubs in the bag is next to impossible. The golfer must also be able to differentiate the thirteen routines and call upon any one of them at random. With many years of endless practice, one may get close to mastering this at a subconscious level.

Even professional golfers at the highest level can win a tournament one week, and then miss the cut the following week. Maintaining the thirteen subroutines is hard. Therefore, throughout the history of the game, people have tried to match golf clubs within a set so that they all will behave as intended, using one swing. One subconscious subroutine could then be utilized for all thirteen clubs. It is much easier to maintain one set of tasks rather than thirteen. This is particularly true when the tasks are so similar that it is difficult to tell them apart.

This discussion does not include the putter, the fourteenth club in the bag, as it uses a fundamentally different set of movement and does therefore not interfere with the mental skills of swinging the thirteen clubs.

Swingweight

Robert Adams developed the first known system for matching golf clubs within a set in the 1920s (U.S. Patent No. 1,953,916, 1934). He measured swingweight, the upward force at the grip end of the club when balanced on a point 14 inches down the shaft on a “Lorythmic” scale using an arbitrary system of letters A to G and numbers 0 to 9, with A0 being the “lightest”, and G9 the “heaviest” (Maltby, 1995). Other scales were developed but none proved popular.

The golf industry currently pays less attention to Swingweight. The Swingweight of every club sold is specified, but it is not unusual to see a set consisting of clubs of various Swingweights. In general, every new development in golf club technology brings the golf club further away from the original wood shafted clubs used for developing the Swingweight method.

Most people do understand that Swingweight does not work, but there is no clear-cut alternative available.

Matching by Moment of Inertia

Instruments for measuring the moment of inertia (MOI) around the grip end of the club are available at a low cost. This has brought about the opportunity of matching a set of clubs by making all the clubs have the same moment of inertia. There are, however, two problems with the current moment of inertia method. First, as will be discussed later, the golf club does not rotate around the grip end of the club, hence the moment of inertia around the grip end is not entirely relevant. Secondly, the system does not specify the mass of the golf club. The importance of mass will be discussed later.

Perfectly Matched Clubs

For the purpose of this paper, *feel* is the forces and moments, from the golf club, that a golfer experiences when holding or swinging a golf club. These forces and moments are felt by the golfer's hands, but also propagate to other parts of the body. When comparing the feel of various golf clubs it is assumed that all the clubs are swung in an identical manner, that is, the torso is applying the same torque for every swing. Identical clubs will then result in equal forces acting on the golfer and thereby provide the same feel.

Per Newton´s laws of motion, to make all the clubs in a set feel the same, whether they are held still or swung, one needs to construct the clubs in such a manner that the following three properties of all the clubs are identical:

1. Mass of the clubs
2. First moment of mass about the center of the grip
3. Second moment of mass about the center of the grip, or MOIG

Such a set of clubs would be quite peculiar and not acceptable by golfers, though such sets were available on the market at one time (Jorgensen, 1999). There is no evidence supporting that such a set would be superior in any way. It is noted that the 2nd criterion, that all the clubs should have the same first moment of mass about the center of the grip, only applies to a club held in a stationary position, so this criterion does not serve much purpose for a golfer swinging a club. The first step in developing the BioMatch method of golf club matching was to create a set of clubs where all the clubs had identical mass and MOIG. This was achieved by altering the mass of the club heads in a standard set of clubs until all the clubs had the same MOIG. Then the overall mass of each club was adjusted by adding a weight inside the shaft at the center of the grip. These clubs worked well. All the clubs had the same feel when being swung by a golfer applying identical swings to each club. The clubs were never marketed as further discoveries and improvements were soon made.

Matching by MOIG

Matching golf clubs by making all the clubs in the set have the same MOIG is as easy as matching by the arbitrary Swingweight method. The longer clubs will automatically be lighter than the shorter clubs, as the club heads of the longer clubs must be lighter to maintain the same MOIG. This makes sense, as will be discovered in the discussion on the BioMatch method below.

The BioMatch Method of Matching Golf Clubs

All the clubs in a set can be made to feel the same when swung by giving all the clubs the same moments of inertia around the rotation point and identical mass. It is here assumed that identical swings are being applied to all the clubs. Earlier attempts to match a set of golf clubs took for granted that all the clubs in the set should *feel* the same. In other words, all the clubs should swing the same. There is no rationale for this to be the case.

Natural Release

It would not make sense for any golfer to try to hold and then actively add torque with the wrists to achieve an increase in clubhead speed. The chances of mistiming the release are too high compared to the possible gain of making it. The natural method of release is the superior way for golfers at all levels (Smith, 2013). Therefore, when developing the BioMatch method of matching golf clubs, the wrists are considered a perfect hinge where no torque is applied in the downswing.

In the BioMatch model, it is assumed that the ideal hinge model is valid over a range of 180 degrees. That is, from the point where the shaft and the left arm form a 90-degree angle in the backswing to the point where the shaft forms a 90-degree angle with the left arm in the follow through. Outside this sector, it is assumed that there is a spring type resistance to hinging any further, created by muscles being stretched outside their usual range of motion.

Applying Newton´s Laws of Motion

To apply Newton´s laws of motion to the golf swing, the downswing can be broken down into two separate motions: the translational motion of the club from the top of the backswing to the impact position and the rotational movement of the club around the center of the grip. The mass of the club is primarily affecting the first, although later it will be shown that lag angle and center of gravity of the club play a minor role as well. The only property of the golf club that affects the rotational motion is the moment of inertia around the center of the grip, referred to as MOIG. Drag forces created by air resistance are not taken into account in the above discussion and will be considered later in this paper.

It is mainly the mass and MOIG of the club that determines how and when the wrists are released for a particular golfer when applying the natural release method. The biomechanical properties of a specific golfer do not naturally change between swings. This brings on a challenge, as typically none of the clubs in a set of golf clubs is matched with regard to mass and MOIG. This causes all the clubs in a set to release differently, which requires the subconscious mind of a golfer to recall automatically how to swing each of the thirteen full swing clubs in a set. If all the clubs had the same mass and MOIG, the golfer would be able to swing at full torque with a natural release without any concern since all the clubs would behave in the same manner. However, as the length of the clubs differs, and the ball position at setup varies, one would not want all the clubs in a set to swing or release identically.

Assume that the optimum hand position at impact for any club is when the left arm and club are aligned in a straight line. For the longer clubs, one therefore wants the wrists to release later in the swing for the hands to be in the correct position at impact. This can be achieved by lowering the mass or increasing the MOIG of the longer clubs. The mass of the club affects the acceleration of the hands in the downswing. The MOIG of the club affects the angular acceleration of the club around the center of the grip. It is, however, not obvious how the optimum mass and MOIG are determined for each club. The physical properties of the golfer in question also come into play.

Path of Club Center of Gravity Relative to Hand Path

The top of the backswing is defined as the point where the hands change direction from moving up to moving down into the downswing. As mentioned above, the wrists are considered to be a frictionless hinge over a sector of 180 degrees in the downswing and follow-through. However, in the backswing the hands set the club in a 90-degree angle to the left arm until the hands start to slow down towards the top of the backswing. From that point forward the wrists will act as a rotational spring. This implies that the higher the MOIG of a club, the further back the golf club will travel at the top of the backswing. How much further depends on the particular golfer´s flexibility in the wrists, in other words, the property of the spring in the wrists. This property is unique to each golfer. In a typical set of golf clubs, the MOIG is larger for the longer clubs, yielding a smaller lag angle at the top of the backswing.

The hands of the golfer do not move in a circular motion around the neck (Nesbit & McGinnis, 2014). The path of the center of the grip is found to have a complex geometry with significantly changing radii, and a constantly moving center-of-curvature during the downswing (Nesbit & McGinnis, 2009). One reason for this is that the hands move in a near perfect circle around the left shoulder socket, which moves in a near circular motion around the neck. The left shoulder socket moves to the left and upward during the downswing, from the golfer´s view. The radius of the path of the hands in the first half of the downswing is considerably larger than the average for the entire downswing. According to measurements carried out by Jacobs (2016) on various golfers the radius during the first phase of the downswing varied between 0.63 and 0.83 m. For the same golfers the radius was reduced to 0.40 m to 0.50 m near the midpoint of the downswing. Due to the large radius at the upper part of the downswing, one may assume that the path of the center of gravity of the club is close to coincide with the path of the center of the grip. It is therefore reasonable to consider the center of gravity of the club to have a distance to the left shoulder socket approximately the same as the center of the grip, until the club starts to release.

Properties of the Human Body

To obtain the optimum mass and MOIG of each club one has to consider the club and the human body in symphony. The dynamic properties of the golfer´s arms must be determined as far as possible without dismantling the golfer (Jorgensen, 1999).

A model of the human body describing the properties of the various body members has to be created. These features include length, mass, center of gravity and moment of inertia of each body member. These properties of the human body members can be estimated based on the height, mass, gender and fat percentage of the person in question (Clauser, McConville & Young, 1969; Drillis & Contini, 1966).

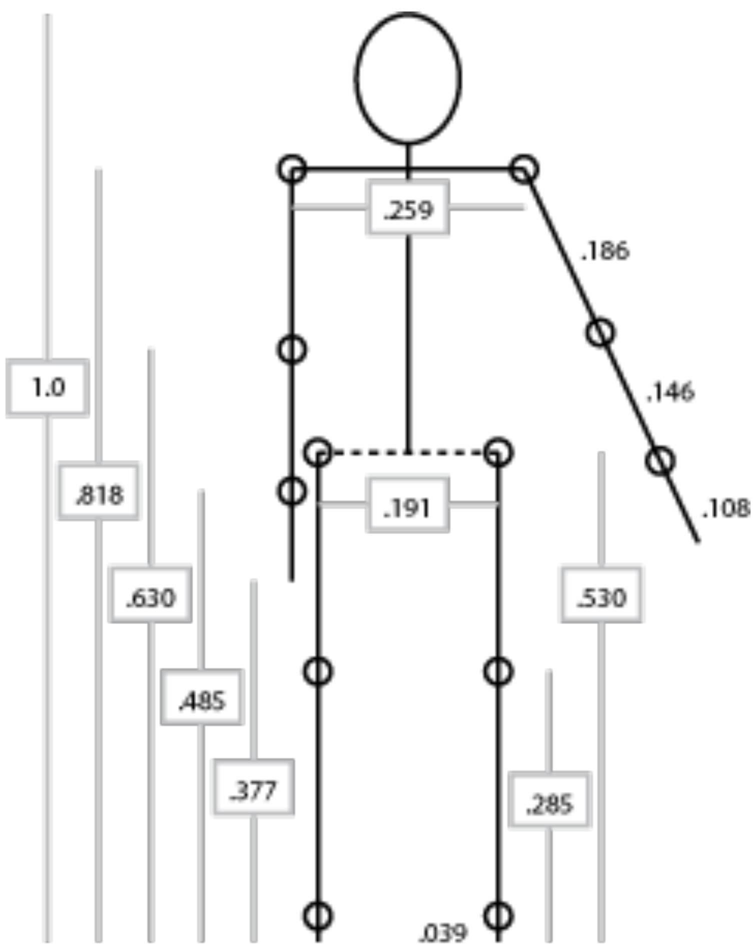

Figure 1. Proportionality constants developed by Drillis and Contini (1966).

Table 1. Properties of Body Members.

Body Member	Mass	Length	Center of Gravity from top
Upper Arm	3.4% of TBM	18.6% of TBH	43% of L_{UA}
Forearm	2.2% of TBM	14.6% of TBH	41% of L_{FA}
Hand (Closed)	0.8% of TBM	5.4% of TBH	50% of L_H
Shoulder Width		25.9% of TBH	

Further to Table 1, it should be noted that the floor to hip joint length is 53.0% of Total Body Height (TBH). The length of the core from hip joint to shoulder intersection at core is 28.8% of TBH. The distance between hip joints is 19.1% of TBH.

It is considered that a person of high body fat percentage will have arms of less relative mass compared to a person of low body fat, as the person will have more mass around the core relative to the arms. The properties of body members provided in Table 3 are based on male subjects. No studies based on female bodies were found. As women in general would be considered to have more mass in the hip and chest regions, they would, in general, have arms of smaller mass than what is indicated in Table 3.

Taking gender and fat percentage into account a new *theoretical total body mass* is introduced as the TBM input for developing the estimated mass of upper arms, forearms, and hands.

Theoretical Total Body Mass = TBM x (1 + (20 – Fat Percentage) / 100) x Gender Factor

The gender factor used is 1.0 for male and 0.9 for female. Some examples:

- A male of TBM 80 Kg and 20% fat will have estimated upper arms of 2.72 Kg.
- A female of TBM 80 Kg and 20% fat will have estimated upper arms of 2.45 Kg.
- A male of TBM 80 Kg and 35% fat will have estimated upper arms of 2.31 Kg.
- A female of TBM 80 Kg and 35% fat will have estimated upper arms of 2.08 Kg.

Mass and MOIG Relation

By considering the principle of conservation of energy, one can make a more elegant model of the golf swing that eliminates calculating all the forces and torques being applied during the downswing. There are five different torques applied to the golf club during the downswing (Jorgensen, 1999). It is outside the scope of this paper to discuss these, and neither is it necessary when applying the principle of conservation of energy.

In the downswing, the center of gravity of the arms and club are close to the neck of the golfer. This gives a small moment of inertia of the arms and club around the neck of the golfer. As the downswing progresses, the arms are extended away from the neck and the moments of inertia of the arms and club about the neck is increasing. The body is applying a constant torque to the arms and club in the downswing (Jorgensen, 1999). Even though the kinetic energy of the system is increasing, the hands will at some point slow down due to the increasing moment of inertia of arms and club around the golfer´s neck. Neck is here defined as the intersection between a line joining the two shoulder sockets and the spine.

Due to the slowing down of the hands of the golfer the club head catches up and swings out, or releases, to impact position. As the club head reaches impact position, the hands can be considered stationary. The core of the body supplies energy to the arms and club during the downswing. This kinetic energy is then transferred into the kinetic energy of the golf club rotating about the center of the grip. Work done on the club = Kinetic Energy at Impact (S. MacKenzie). Assuming that the hands are considered stationary at impact, all the kinetic energy created has been transferred to the rotational energy of the club. It is thereby implied that: Energy generated by the applied torque during the downswing = Kinetic energy of the arms and club just before release = Kinetic energy of golf club just before impact.

Ball Position

It is assumed that the driver impacts the ball when it is perpendicular to the target line. This gives a ball position just inside the left foot. It is further assumed that for the shortest club in the set, the ball is placed in the middle of the stance. The BioMatch method calculates the appropriate ball positions for all the clubs according to the address position, which is determined based on length and lie angle of clubs, as well as the estimated dimensions of the golfer.

Considering Biomechanics

The shaft of the club and the left arm are considered to be in a straight line for optimum impact position. This means that the hands are more in the middle of the stance for the short clubs and further forward for the longer clubs. This again implies that the hands swing through a shorter sector for the shorter clubs. Assuming that the body applies the same torque for every swing, the shorter clubs must have a larger mass for the hands to reach the correct impact position in the same amount of time.

The properties of the upper arms, the forearms, and the hands need to be calculated. The core including the shoulders are considered the engine of the model. Total Body Mass is abbreviated TBM, Total Body Height is abbreviated TBH, and Moment Of Inertia is abbreviated MOI. Table 2 contains additional abbreviations.

Table 2. Abbreviations.

Body Member	Mass	Length	CG from Top	CG from Spine	Moment	MOI	MOI around Spine
Upper Arm	M_{UA}	L_{UA}	CG_{UA}	CGS_{UA}	MOM_{UA}	MOI_{UA}	$MOIS_{UA}$
Forearm	M_{FA}	L_{FA}	CG_{FA}	CGS_{FA}	MOM_{FA}	MOI_{FA}	$MOIS_{FA}$
Hand (Closed)	M_H	L_H	CG_H	CGS_H	MOM_H	MOI_H	$MOIS_H$
Shoulder Width		L_{SW}					

The BioMatch computer program creates an anthropometric model of any particular golfer. Together with the properties of the golfer´s clubs, the program calculates the optimum mass of each golf club in the set. Mass can be adjusted by adding weight to the grip end of the club. This is the best location for adding mass, as it will have minimal impact on MOIG. The optimal mass is a function of the MOIG as well as length and lie angle of each club and the physical properties of the golfer.

Drag Forces

The drag force, created by air resistance, opposing the movement of the clubhead through the air is taken into account in the BioMatch computer program. Estimated height and width of the club heads, as viewed from down the target line at set-up, is entered into the program. The product will give the effective area as related to air resistance. A form factor of each clubhead is also entered for the program to calculate their drag force. The program uses typical measurements by default. The drag forces of the shafts are ignored, as it is very much the same from club to club.

Computer Application

There are two groups of input data to be entered in the BioMatch computer application, particulars of the golfer and details of the golf clubs to be matched. Particulars for the golfer are height, weight, gender, and fat percentage. The details of the clubs to be entered are the mass, MOIG, length, and lie angle of each golf club in the set to be matched. Users of the program that do not have access to an instrument for measuring the MOIG of the golf clubs will have the MOIG estimated based on length, mass, and a database of typical clubhead masses for each club. Typical values for lie angles are used as the default. Default values of club head dimensions are utilized, unless specified by the user, to calculate drag.

The BioMatch program will determine the size of weight to be added to each club. In the online version of the BioMatch program, weights of the correct size can be automatically ordered through Rational Golf LLC. Smaller and weaker golfers should consider changing the grips to lighter options before the BioMatch method is applied, as this will reduce the overall mass of the final set of clubs. The BioMatch method should be implemented after club fitting, the traditional selection of shafts, grips, clubheads, club lengths, lie angles, and loft angles.

BioMatch Calculations

Assumptions

To apply physics to the golf swing, some assumptions are made.

- The golf club is an extension of the left arm at impact. That is, the left shoulder, hands, and clubhead are in a straight line at impact.
- The left arm swings around the left shoulder. The shoulders turn around the neck.
- The mass and centers of gravity of the human body components are established according to the earlier chapter on Properties of the Human Body.
- Air resistance is calculated and taken into account for the club heads. As the air resistance of the other moving parts is quite small in comparison, these are ignored in these calculations.
- Due to the large radius of the path of the hands during the upper part of the downswing, it is assumed that the path of the center of gravity of the club coincides with the path of the center of the grip. The center of gravity of the various clubs is assumed to travel on the same path in the initial part of the downswing. This as the clubs with the greatest distance between the center of the grip and the club´s center of gravity are the clubs with the largest MOIG, and thereby a smaller lag angle at the top of the backswing. The mass of the club is assumed to be in the hands of the golfer until the club releases.

Moment of Inertia of Clubs about Grip Center

For all the clubs to rotate around the center of the grip in an identical manner, the Moment of Inertia about the grip center (MOIG) must be the same for all clubs. However, when considering air resistance, it is found that the clubs must have small variations in MOIG in order for the club heads to be delivered to the impact point at the same moment in time. This has, in particular, an impact on the driver due to the large modern driver heads.

Individual club MOIG + Correction for air resistance = MOIG Constant (1)

Or

Individual club MOIG = MOIG Constant - Correction for air resistance (2)

"MOIG Constant" is the MOIG of the club with the lowest MOIG without considering the air resistance. The club with the lowest MOIG in a traditional set of golf clubs is normally the shortest club. The MOIG can be obtained by measurement using a suitable MOI measuring device, or it can be calculated as the sum of the MOI of all the clubs components about the center of the grip.

Correction for air resistance Calculation

Maximum club head speed is measured of the individual golfer using a club of a measured length. Once the club head speed at impact is established, the angular velocity, ω, at the time of impact can be calculated as:

$$\omega = \frac{v}{r} \tag{3}$$

Where,

- v = club head speed at impact
- r = club length measured from the center of the grip

Angular Acceleration, α, is found from Newton's laws of motion:

$$\omega = \omega_0^2 + 2\alpha\theta_C \tag{4}$$

Where,

- ω = Angular velocity at impact
- ω_0 = Initial angular velocity
- α = Angular acceleration
- θ_C = Angle in which the club rotate around the center of the grip from the top of the backswing to point of impact.

As the initial velocity at top of the backswing is zero, angular acceleration from top of the backswing to impact is calculated as follows:

$$\alpha = \frac{\omega^2}{2\theta} \tag{5}$$

Air resistance, drag, is a force acting in the opposite direction of the club head movement.

$$f_{drag} = \frac{1}{2}C\rho A v^2 \tag{6}$$

Where,

- C = drag coefficient
- ρ = air density, approximately 1.29
- A = cross-sectional area from front view

The drag coefficient of each club head must be estimated or established by testing. A simple estimation based on the following values may be sufficient. The drag coefficient is 0.5 for a sphere and can reach 2 for irregular shapes. One may generalize as follows:

Drag coefficient for Irons = 0.90

Drag coefficient for Hybrids = 0.75

Drag coefficient for Woods = 0.63

Drag coefficient for Driver = 0.60

The above are general estimates. Better estimates can be obtained by testing of the actual club heads being fitted.

The Maximum Torque around the grip center created by the drag, opposing the movement of the club, is as follows:

$$\tau_{drag\,\max} = f_{drag\,\max} \times lever \tag{7}$$

Where the lever is the distance from the center of grip to the geometric center of the club head.

The average Torque created by air resistance can be estimated to be half of the Maximum Torque. More exact results can be achieved by applying advanced calculus. Therefore:

$$\tau_{drag} = \frac{\tau_{drag\,\max}}{2} \tag{8}$$

By applying Newton's second law of circular motion:

$$MOIG_{correction} = \frac{\tau_{drag}}{\alpha} \tag{9}$$

The optimum MOIG of each club can thus be determined as:

$$\mathrm{MOIG_{Individual}} = \mathrm{MOIG_{Constant}} - \mathrm{MOIG_{Correction}} \tag{10}$$

It was, however, found that the results of these calculations are independent of the club head speed. There is thereby no need to enter the club head speed as it cancels itself out in the calculations. The v^2 part of the τ_{drag} is proportional to the ω^2 in the α of the above equation for $MOIG_{correction}$. Thus there is no need to adjust clubs as the golfer learns to obtain higher club head speeds.

Mass of Clubs

Basic Principles Describing Mass

For the hands to come to the same position at impact for all the clubs, all the clubs should have the same mass. However, we do want the hands to be a bit more forward at impact for the longer clubs. We therefore have to include a correction for the hand position when considering the mass of each club. The longer clubs leave the hands further forward as the club is an elongation of the left arm. For the driver, the ball is positioned further forward in the stance compared to the shorter clubs.

Therefore:

Total Club Mass - Correction for hand position = Constant throughout the set (11)

Or

Total Club Mass = Constant throughout the set + Correction for hand position (12)

Correction for hand position is set to zero for the longest club. The *Constant mass throughout the set of Golf clubs* thereby equals the mass of the longest club. No correction mass is added to the longest club. The shorter the club, the heavier it needs to be in order to slow down the hands in the downswing sufficient to end up in the correct position at impact.

Center of Gravity of the Various Body Members Relative to the Neck

The Center of Gravity of the various body members from the neck is calculated using geometry as follows.

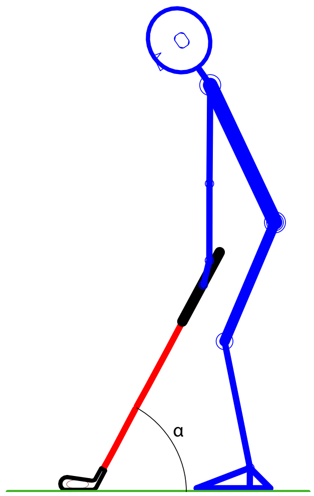

Figure 2. Golfer in side view with a typical 7 Iron.

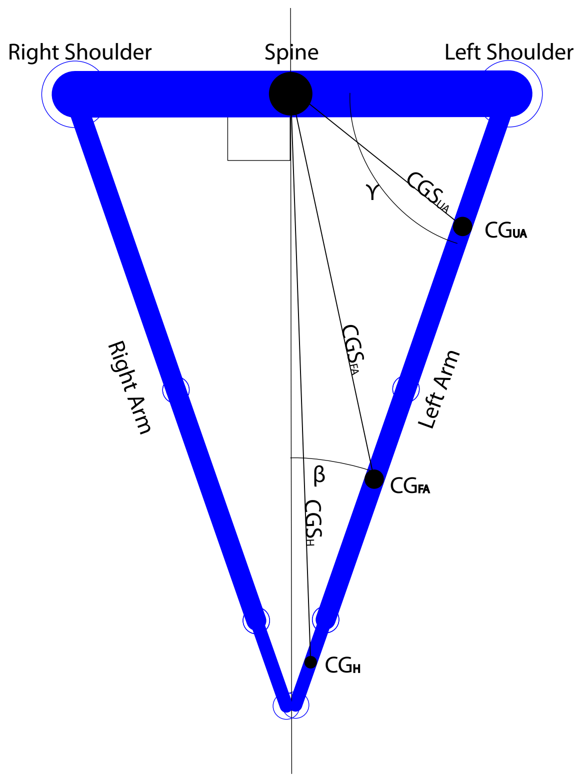

Figure 3. Centers of gravity with distances to the neck at impact position.

$$\beta = \tan^{-1}\left(\frac{L_{SW}}{2\left(L_{UA} + L_{FA} + L_{H}\right)}\right) \tag{13}$$

$$\gamma = 180^\circ - 90^\circ - \beta \tag{14}$$

Using Law of Cosines;

$$c^2 = a^2 + b^2 - 2abCosC \tag{15}$$

$$CGS_{UA} = \sqrt{\left(\frac{L_{SW}}{2}\right)^2 + CG_{UA}^2 - L_{SW} \times CG_{UA} \times Cos\gamma} \tag{16}$$

$$CGS_{FA} = \sqrt{\left(\frac{L_{SW}}{2}\right)^2 + \left(L_{UA} + CG_{FA}\right)^2 - L_{SW} \times \left(L_{UA} + CG_{FA}\right) \times Cos\gamma} \tag{17}$$

$$CGS_{H} = \sqrt{\left(\frac{L_{SW}}{2}\right)^2 + \left(L_{UA} + L_{FA} + CG_{H}\right)^2 - L_{SW} \times \left(L_{UA} + L_{FA} + CG_{H}\right) \times Cos\gamma} \tag{18}$$

The Moment of Inertia of the body members around their center of gravity is estimated as follows:

$$MOI_{UA} = \frac{M_{UA} \times L_{UA}^2}{12} \tag{19}$$

$$MOI_{FA} = \frac{M_{FA} \times L_{FA}^2}{12} \tag{20}$$

$$MOI_{H} = \frac{M_{H} \times L_{H}^2}{12} \tag{21}$$

The above is not exact, as the center of gravity does not coincide exactly with the midpoint of the member. This has, however, a negligible effect on the overall calculations of optimum club mass.

The Moment of Inertia of the body members around the spine is calculated as follows:

$$MOIS_{UA} = MOI_{UA} + M_{UA} \times CGS_{UA}^2 \tag{22}$$

$$MOIS_{FA} = MOI_{FA} + M_{FA} \times CGS_{FA}^2 \tag{23}$$

$$MOIS_H = MOI_H + M_H \times CGS_H^2 \tag{24}$$

The total Moment of Inertia of the left arm around the spine, as shown in figure 4, is therefore:

$$MOIS_{\mathrm{Im}\,pact} = MOIS_{UA} + MOIS_{FA} + MOIS_H \tag{25}$$

This is the Moment of inertia of the left arm around the spine at the impact position.

At top of the backswing

The Moment of inertia of arms around the spine at the top of backswing position is considerably less, as can be seen in figure 5.

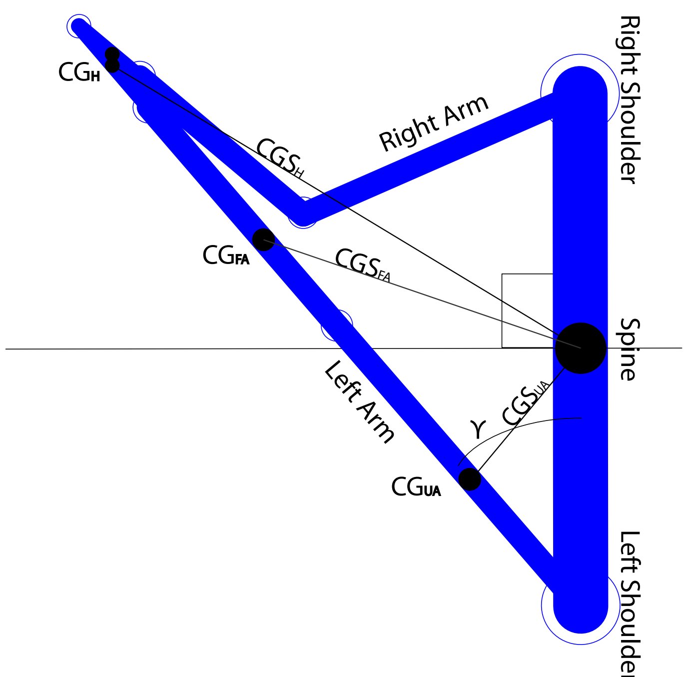

Figure 4. Centers of gravity with distances to the spine at top of the backswing.

As can be seen from figure 4, the angle between the shoulders and left arm is now reduced by 30°. This is an approximation and may vary slightly from golfer to golfer.

Again Using Law of Cosines;

$$c^2 = a^2 + b^2 - 2abCosC \tag{26}$$

For Left Arm

$$CGS_{UA} = \sqrt{\left(\frac{L_{SW}}{2}\right)^2 + CG_{UA}^2 - L_{SW} \times CG_{UA} \times Cos(\gamma - 30°)} \quad (27)$$

$$CGS_{FA} = \sqrt{\left(\frac{L_{SW}}{2}\right)^2 + \left(L_{UA} + CG_{FA}\right)^2 - L_{SW} \times \left(L_{UA} + CG_{FA}\right) \times Cos(\gamma - 30°)} \quad (28)$$

$$CGS_{H} = \sqrt{\left(\frac{L_{SW}}{2}\right)^2 + \left(L_{UA} + L_{FA} + CG_{H}\right)^2 - L_{SW} \times \left(L_{UA} + L_{FA} + CG_{H}\right) \times Cos(\gamma - 30°)} \quad (29)$$

The Moment of Inertia of the body members around their center of gravity is estimated as follows:

$$MOI_{UA} = \frac{M_{UA} \times L_{UA}^2}{12} \quad (30)$$

$$MOI_{FA} = \frac{M_{FA} \times L_{FA}^2}{12} \quad (31)$$

$$MOI_{H} = \frac{M_{H} \times L_{H}^2}{12} \quad (32)$$

The above is not exact, as the center of gravity does not coincide with the midpoint of the member. This has negligible effect on the overall club mass calculations.

The Moment of Inertia of the body members around the spine is calculated as follows:

$$MOIS_{UA} = MOI_{UA} + M_{UA} \times CGS_{UA}^2 \quad (33)$$

$$MOIS_{FA} = MOI_{FA} + M_{FA} \times CGS_{FA}^2 \quad (34)$$

$$MOIS_{H} = MOI_{H} + M_{H} \times CGS_{H}^2 \quad (35)$$

The total Moment of Inertia of the left arm around the spine, as shown in figure 5, is thereby:

$$MOIS_{\mathrm{Im}\,pact} = MOIS_{UA} + MOIS_{FA} + MOIS_{H} \quad (36)$$

Correction of Club Mass due to Angle of Impact

The ball is typically positioned in the middle of the stance for the shortest club and inside the left foot for the Driver. This gives a difference in ball position of 174 mm for a person of 1800 mm height. Assuming that feet are shoulder width apart, the center of the feet is 1800 mm x 0.259 = 466 mm apart. Assume that the width of the shoe is 118 mm for a person of 1800 mm height. The distance from the center of the stance to the inside of the left foot is then 466 mm / 2 - 118/ 2 = 174 mm.

Difference in ball position (L_{BP}) thereby becomes TBH [mm] x 174 / 1800. Alternatively, the difference in ball position may be measured for the actual golfer. Variations in stance width from club to club can also be taken into account.

The distance from the ball to left shoulder joint is needed for calculating the optimal hand position at impact. From Figure 1 it can be seen that this distance equals:

$$L_{BS} = \sqrt{\left(L_C \times Cos\alpha\right)^2 + \left(L_C \times Sin\alpha + L_{UA} + L_{FA}\right)^2} \quad (37)$$

Where $\alpha = LieAngle$.

Impact angle also needs to be considered. This is defined as the angle between the ground and the forward side of the club shaft at impact, as illustrated in figure 6. This angle is 90 degrees when the club shaft is perpendicular to the target line at impact. This will be the case for the driver; for all the other clubs the angle will be less than 90 degrees.

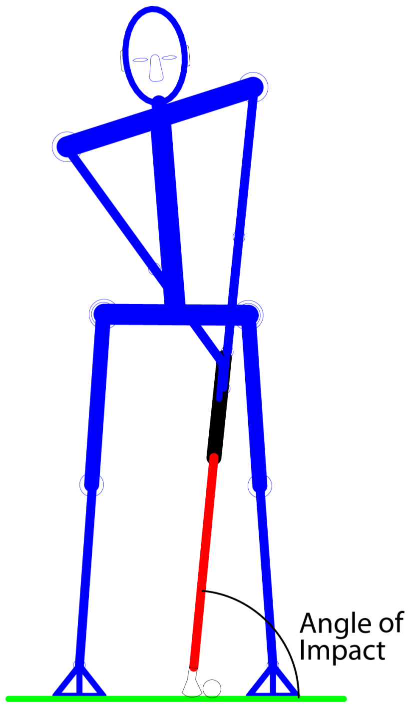

Figure 5. Angle of impact.

Angle of impact, δ, is thereby calculated as follows:

$$\delta = Tan^{-1}\frac{L_{BS}}{L_{BD}} \quad (38)$$

Where L_{BD} is the distance between the ball position for the club in question and that of the driver.

For each particular club the ball position, L_{BD}, is calculated as follows:

$$L_{BD} = \frac{L_{BP} \times L_{Dr}}{L_{Dr} - L_{SC}} - \frac{L_{BP} \times L_{AC}}{L_{Dr} - L_{SC}} \quad (39)$$

Where;

- L_{AC} = Length of Actual Club in question.
- L_{SC} = Length of the shortest club in the set.
- L_{Dr} = Length of the longest club in the set, the driver.
- L_{BP} = Distance from ball position for the driver to ball position for Shortest Club.

The sector that the left arm is sweeping in the downswing equals the angle between the left arm at top of the backswing and the horizontal plus the angle of attack. Let us denote the angle between the left arm and the horizontal ε. This angle is simply 90 degrees minus γ, as shown in figure 4. Note that the left arm is raised 30 degrees relative to the shoulders at the top of the backswing. Alternatively, the angle between the left arm and the horizontal, ε, can be measured for the individual golfer using video. It is assumed that golfers will have the same length of backswing for all the clubs. This is consistent with the proposed theory that one swing shall fit all clubs.

Swing Sector

$$\text{Swing Sector} = \delta + \varepsilon + \phi = \delta + 90^\circ - \gamma + 30^\circ + \phi \tag{40}$$

Where ϕ is the component of swing sector due to ball position.

$$Sin\phi = \frac{L_{BP} - L_{BD}}{L_{BS}} \tag{41}$$

Moment of Inertia of Left Arm

The average moment of inertia of the left arm around the spine as it moves through the downswing is given as $MOIS_{Arm}$.

$$MOIS_{Arm} = \frac{MOIS_{Top} + MOIS_{Impact}}{2} \tag{42}$$

This gives the average value of the MOIS at the top of the backswing and the MOIS at the point of impact. In reality, the MOIS changes throughout the downswing. By applying advanced calculus, more exact calculations can be obtained.

Moment of Inertia of the left arm and club as they swing through the swing sector around the spine is denoted $MOIS_{System}$.

$$MOIS_{System} = MOIS_{Arm} + MOIS_{Club} \tag{43}$$

$MOIS_{Club}$ = Mass of Club x (Distance from Spine)^2 (44)

As earlier discussed the distance from the spine to the center of gravity of the club at the top of the backswing can be assumed to be the same for all the clubs, this as the longer clubs have a smaller lag angle. If, for example, the distance from the spine to the center of gravity of the clubs are CGS_H multiplied by a factor of 1.3, the factor will cancel itself out in equations (43) and (44). This was tested using the computer application. The resulting optimum club weights were exactly the same whether the factor applied was 1, 1.3, or even 10. Therefore, CGS_H is used as the Distance from Spine to the center of gravity of the club before release in all calculations.

The time taken from the top of the backswing to impact should be the same for all the clubs. This is consistent with the "one swing for all the clubs" concept. To achieve this, the various clubs must have different mass depending on the position of the hands at impact. The Torque applied by the body must also be the same for all the clubs in order to satisfy the “one swing for all the clubs” concept. Torque is denoted by τ. According to Newton’s second law:

$$\tau = MOIS_{System} \times \alpha = C \tag{45}$$

Where;

- α is the angular acceleration.
- C is a constant that is the same for all the clubs in a matched set.

Further;

$$\Theta = \frac{1}{2}\alpha t^2 \qquad \text{or} \qquad \alpha = \frac{2\Theta}{t^2} \tag{46}$$

where Θ is the Swing Sector.

$$\tau = MOIS_{System} \times \frac{2\Theta}{t^2} = C \tag{47}$$

The time taken for completing the downswing, t, is constant throughout the set of clubs. Thereby it is given that:

$$MOIS_{System} \times \Theta = C \tag{48}$$

This implies that as the swing sector is increased, the mass of the club has to be reduced in order to complete the downswing in the same time for all the clubs. One may calculate C for one club, then work backward and calculate $MOIS_{System}$ for all the other clubs. From $MOIS_{System}$ the corrected mass of each club can be calculated.

BioMatch Index

During the studies leading up to the invention of the BioMatch method, it was proven that the BioMatch Index (BMI) = MOIG / mass is constant for all clubs that swing identically. Every club in the set will have a unique BMI. Any club altered with regard to MOIG and mass, will behave in an identical manner as long as the BMI is maintained. For example, if the BioMatch report specifies that a weight of certain mass be added to a club, the mass can be reduced if the MOIG is reduced accordingly. BMI is a measurement of how a golf club behaves, or releases when swung.

Developing the Theory

The above BioMatch Index theory is arrived at by considering conservation of energy. For rotation of objects, the net work is equal to the change in rotational kinetic energy:

$$W_{net} = \frac{1}{2} I\omega_f^2 - \frac{1}{2} I\omega_i^2 \tag{49}$$

Where

- W = Work
- I = moment of inertia
- ω = angular velocity

Subscript *f* refers to *final*, and subscript *i* refer to *initial*.

As the angular velocity at the top of the backswing is zero, so is the initial kinetic energy. Kinetic rotational energy thereby becomes:

$$E_K = \frac{1}{2} I\omega^2 \tag{50}$$

Where

- E_K = Kinetic Energy

For a constant torque, the work can be expressed as:

$$W = \tau \text{ x } \theta \tag{51}$$

Where

- τ = torque
- θ = the angle through the torque is applied

The work exerted by the body can be described as the torque applied by the user through an angle from the top of the backswing to the point of impact. The torque applied by the body must be the same for all the clubs in order to satisfy the “one swing for all the clubs” concept.

The movement of the golf club, in the downswing, consists of two movements imposed on each other: a translational movement of the club around the left shoulder and the rotation of the club around the center of the grip position on the club. The kinetic energy related to the translational movement of the club around the left shoulder is:

$$E_{KH} = \frac{1}{2} I\omega^2 = \frac{1}{2} M_{c\,\mathrm{lub}} L_A^2 \frac{v_H^2}{L_A^2} = \frac{1}{2} M_{c\,\mathrm{lub}} v_H^2 \tag{52}$$

Where

- E_{KH} = kinetic energy related to the translational movement of the club.
- L_A = the length of the left arm, as measured from the shoulder socket to the center of the grip.

- M_{club} = Total mass of the golf club
- v_H = velocity of hands

The length L_A is also taken as the approximate distance from the left shoulder socket to the center of gravity of the club before the club release. This may very well hold true for some golfers; for most golfers this will just be an approximation.

For the rotation of the club around the center of the grip position on the club, the energy is:

$$E_{KClub} = \frac{1}{2} I\omega^2 = \frac{1}{2} MOIG \frac{v_{CH}^2}{L_{CE}^2} \tag{53}$$

Where

- E_{KClub} = kinetic energy related to the rotational movement of the club around the center of the grip.
- L_{CE} is the club length from the grip center down to the lower end of the club, or effective length of Club.
- v_{CH} = velocity of the club head

Based on the principle of conservation of energy the sum of the above two must be equal to the work exerted by the user. The work exerted by the user is a constant describing the abilities of the user with a club of a particular length. Note that the work exerted by the user differs from club to club, as clubs of different lengths have different angles of θ. Thereby:

$$\frac{1}{2} M_{Club} v_H^2 + \frac{1}{2} MOIG \frac{v_{CH}^2}{L_{CE}^2} = Constant \tag{54}$$

During most of the downswing, the E_{KH} is the dominant part. However, as the club is released the E_{KClub} becomes the dominant part as the velocity of the hands approaches zero at impact. All the work done on the club will go into the E_{KH}, and then at the very end, all this energy is transferred into E_{KClub}. As such:

$$\frac{1}{2}M_{C\,\mathrm{lub}}v_H^2 = \frac{1}{2}MOIG\frac{v_{CH}^2}{L_{CE}^2} \tag{55}$$

For some proficient golfers, the velocity of the hands is close to zero at impact. Nevertheless, it is irrelevant how the club releases through the downswing; the principle of conservation of energy remains. It is assumed that a less proficient golfer will have the same amount of inefficiency with regard to energy transfer to the club throughout the set of clubs. This inefficiency is then a constant specific to each golfer. This constant will then be part of the constant C_{Golfer} described below.

It is important to clarify that the principle of conservation of energy applies even though the hands do not come to a complete standstill at impact and the club does release throughout the downswing. The rotational kinetic energy of the golf club plus the kinetic translational energy of the golf club equals the total kinetic energy transferred to the club.

Also, assuming the downswing is arching θ degrees and that the downswing is carried out in t seconds. Then

$$v_H^2 = \frac{\theta \times L_A}{t} \tag{56}$$

It is noted that θ, L_A, and t are all factors specific to the user. Therefore, v^2_H can be substituted with a Constant specific to the particular user called C_{Golfer}.

Then

$$\frac{1}{2}M_{C\,\mathrm{lub}} \times C_{Golfer} = \frac{1}{2}MOIG\frac{v_{CH}^2}{L_{CE}^2} \tag{57}$$

Hence,

$$C_{Golfer} = \frac{MOIG \times v_{CH}^2}{M_{C\,\mathrm{lub}} \times L_C^2} \tag{58}$$

Given the preceding equation, it should be noted that:

- By decreasing the MOIG, the club head speed is increased. One should therefore seek to minimize the MOIG throughout the set of golf clubs. Although a certain club head weight needs to be maintained in order to provide an efficient energy transfer to the golf ball.
- By increasing the mass of the club, the club head speed correspondingly increases. There will, however, be a point where the user would not be able to swing the club efficiently.
- By increasing the length of the club, the club head speed correspondingly increases.

Thus, it should be noted that the weight of the club should be manageable and that shaft and club head mass should be minimized to maximize clubhead speed. Furthermore, it should be noted that V_{CH} is proportional to L_{CE}. That is V_{CH}^2 / L_{CE}^2 is a constant. Correspondingly, we can define a new Constant BioMatch Index or BMI as MOIG/M_{Club}.

$$BMI = BioMatch - Index = \frac{MOIG}{M_{C\,\mathrm{lub}}} \tag{59}$$

If the BMI were made to be constant throughout the set of golf clubs, all the clubs would behave identically when swung. However, due to different target hand positions at impact, different length of clubs, and different drag forces for each club, the BMI will be different for every club. When the optimum mass and MOIG has been determined for each club in the set through the BioMatch method, the optimum BMI for each club can be determined.

Optimizing Mass of each Club

The above BioMatch calculations specify the optimum MOIG and Mass of each club in the set of clubs. It would be impractical to produce a set of clubs with specific MOIG and Mass of each club in the set for each user. This is where the BioMatch index becomes useful. The optimum BioMatch index can be determined for each club from the optimum MOIG and optimum Mass of each. The optimum MOIG will normally differ from the actual MOIG. By rearranging the BioMatch Index formula, a new optimum mass based on the actual MOIG can be calculated:

$$M_{Club} = MOIG_{Actual} \,/\, \text{BioMatch-Index} \quad (60)$$

This means that whatever the MOIG of the clubs in a set is, the correct BioMatch-Index can be obtained by adjusting the mass of each club only. Any set of clubs can be matched, according to BioMatch method by adjusting the mass only. The optimum mass for each club can be obtained by adding a weight of specific mass to the grip end of each club.

Demonstrating the BMI concept

In the BioMatch patent document (U.S. Patent No. 9,022,878, 2015), BioMatch Index (BMI) is defined as: BMI = BioMatch-Index = MOIG/ M_{Club}

A typical golfer is used in the following example to demonstrate the BMI formula:

- Height 1800 mm
- Mass 80 Kg
- Fat 25%
- Gender Male

By making variations in the MOIG of a club in the set matched for the above golfer, the corresponding mass of each club is calculated using the BioMatch program. In this example, the MOIG of the 7-iron is varied from its original value. Values of MOIG entered for the 7-iron into the BioMatch program range from -20% to +20% relative to the originally measured value of MOIG. The resulting table is presented in Appendix A.

The resulting mass of the club is plotted on a graph as a function of the various values of MOIG. The graph is provided in Appendix B. The linear relationship between mass and MOIG confirms that the BioMatch-Index = MOIG/ M_{Club} = Constant.

Why BioMatch Works

According to neuroscience research, it takes a high level of focus during practice to develop and reinforce the kinesthetic memory of a good golf swing. To establish kinesthetic memory, one has to practice the same stroke repeatedly to carve the neural pathways (Zumerchik, 2010) that constitute muscle memory.

As golfers carry 13 full swing clubs in their bags, they have to develop muscle memory for 13 different swings. Further, the golfers´ subconscious minds have to be able to tell them apart as they pick up a club. The golfer´s conscious mind knows what club is being hit next; this must also be picked up by the golfer´s subconscious mind to bring the correct set of muscle memory into focus.

The traditional waggle of the club before the swing is performed helps in a variety of ways. It assists the golfer to recognize the physical properties of the club in question, particularly the length of the club and the lie angle of the club. It brings forward the correct set of swing mechanics, and establishes the rhythm and timing required to get the muscles moving in the correct pattern and sequence. Good golfers perform the swing without interference from the conscious mind and only concentrate on the target (Zumerchik, 2010).

For each new club to be hit the neurons undergo a reorganization (Zumerchik, 2010). One may appreciate the complexity of this process and how it may cause errant, or at least less than perfect shots. What if the mind only had to deal with one set of properties that were identical throughout the set of clubs? The golfer would only have to ingrain one, rather than thirteen sets of muscle memories, which also has to be distinguishable at short notice. This is exactly what the BioMatch method does, as the correct MOIG and mass are applied to all the clubs. Once a golfer has set up to a shot, no matter which club is used, the golfer can simply apply the one and only full swing ingrained. The phenomenon can be observed on any driving range. A golfer may hit 50 good shots in a row with a 9-iron, then pick up a 3-wood and hit a couple of errant shots before being able to perform some consecutive good shots. Unfortunately, out on the course, the golfer seldom uses the same club twice in a row. This strains the subconscious mind and causes all sorts of errors. This is one reason it is difficult to take the game from the driving range onto the golf course.

By having the clubs in the set matched by the BioMatch method, the subconscious mind only has to deal with one swing. Once the subconscious mind gets accustomed to and learns to trust the clubs behaving as intended without any effort on its part, the game becomes easier and less stressful to play.

Earlier Studies on Matching of Golf Clubs

A study carried out by Sasho J. MacKenzie, Keisten Wilson, and Daniel E. Boucher compare Swingweight matched iron clubs with sets of irons matched by moment of inertia (MOI). MOI is measured about an axis through the end of the grip. The paper does not consider the other property of the club that affects its movement in the downswing, namely mass. Only the irons were considered in this study.

The study concluded that none of the methods had any advantage over the other. It does mention that this could be because the participant were used to playing with clubs matched by Swingweight and that the players had tailored their swing to Swingweight matched clubs.

In the above study the mass of each club was random and its effect was not measured. The current paper study the effect of mass on golf clubs while the MOI measured about the center of the golfers grip (MOIG) is kept essentially constant.

Testing of BioMatch

To prove the effectiveness of the BioMatch method, it needs to be tested on proficient golf players. Small scale testing indicates that distance and accuracy is improved effortlessly over a short time. Some subjects show instant improvement in distance and accuracy. Users of the BioMatch system consistently report a drastic improvement in their game.

Adding mass to a club can have two outcomes:

1. If the speed of the hands is maintained, the kinetic energy at impact is increased and thereby the club head speed is increased.
2. If the speed of the hands is slowed down, the hands will be further back at impact resulting in a higher launch angle and higher ball flight. The spin axis is also moved in the negative direction causing more of a draw.

Testing confirms a combination of the two outcomes. There is some increase in club head speed and some increase in launch angle. The result is more evident in some players than others. Players who are steering the club with their wrists see little of the effects of BioMatch. Players who trust their swing and play with loose wrists will experience the effects notably. The younger, more athletic, and more proficient golfers see a gain in club head speed and distance as well as their angle of attack getting more in line with the theoretical optimum prescribed by BioMatch. As the subjects continue to practice, their launch angle moves back towards their optimum, resulting in a more penetrating and longer ball flight.

Research Proposal

A large-scale test is proposed in which subjects will hit a predetermined number of balls with each of their clubs. After hitting each ball, the subject will change to another club. This will continue until the subject has hit a predetermined number of balls with each club in a predetermined order. Variables such as angle of attack, carry distance, carry side, total distance, max height, direction, spin, spin axis, etc. should be measured for each shot. The angle of attack should be compared to the angle that the BioMatch system advocates for each club. Consistency in direction and distance should be calculated for each club. Each subject carries out the same procedure.

The experiment needs to be carried out under consistent conditions. That means that subjects will hit balls off a mat indoors. Data will be gathered from measurements made with a trustworthy instrument, such as the Trackman Doppler radar launch monitor.

The next step would be to modify the subjects´ golf clubs according to the BioMatch method and repeat the same procedure. The players will continue to use their modified clubs in practice over the next two weeks. Then the same routine is repeated with the modified clubs. The experiment may also be repeated after, say, six weeks. A full research proposal is available from the author on request. The author will support any organization that would like to carry out such testing.

Testing carried out by GolfTest USA

GolfTest USA carried out testing of the BioMatch method in Arizona during the winter of 2017 / 2018. The report issued by GolfTest USA is included in Appendix ??. My comments to the report is attached in Appendix ?? GolfTest USA reports an average increase in distance of 3.5% and an average improvement in dispersion of 2.9%. The protocol of the Research Proposal was not followed and the quality of subjects is questionable.

However, there was a significant increase in average maximum height of just over 10% as well as an increase in launch angle of just over 6%. Both findings supports the BioMatch theory that the increased overall club mass will slow down the hands and thereby position the hands further back at impact. This will, as the testing suggests, give a higher launch angle and higher maximum ball height. With the data provided it was not possible to draw any conclusion on how much closer the angle of attack moved towards the angle prescribed by the BioMatch method.

Testing carried out by the Author

All the subjects in the below tests are playing with properly fitted golf clubs matched by Swingweight. The test set out to determine the effect of variations in mass of golf clubs on angle of attack, face angle, dynamic loft, Spin axis, maximum flight height, carry, and side as well as the consistency in the above parameters.

Testing with Professional Coaches

I carried out testing according to the Research Proposal using four professional coaches as subjects. The lack of consistency in their shot making as well as a lot of missing data from the Trackman made it difficult to determine the changes in relevant parameters such as angle of attack. However, some findings are consistent.

The trend line of angle of attack plotted against club length moves closer to the angle of attack prescribed by BioMatch. After the subjects had used the matched clubs for a couple of rounds the angle of attack graph moved half way from the original angle to that of the target graph prescribed by BioMatch. The more the subjects had played after having their clubs matched, the closer to the target line they got. This indicates that the effects of BioMatch become more prominent with practice. This, assumingly, as the subconscious mind get accustomed to the clubs and thereby start to play with looser wrists.

The dynamic loft increased by an average 1 degree? after the subjects had used the BioMatch clubs for a couple of rounds. The face angle changed about 1 degree from slightly open to slightly closed. As the hands slow down the clubface is given more time to rotate. Spin axis turned 1.5 degree towards a draw. Average maximum flight height increased from 22.7 to

24 yards. Ball landed on average 3 yards more to the left. As a result of the higher launch angle the ball carry decreased by almost 3 yards in this group. Standard deviation in launch direction decreased from 1.6 to 1.2 degrees. Standard deviation in launch angle decreased from 1.4 to 1.0 degrees. All these findings support the BioMatch method of matching golf clubs. The quality of data is however of such a nature that this should be considered an indication that the BioMatch method works, rather than definite proof.

Per 100 gram of mass added to a club:

- The average angle of attack was reduced by 0.9 degrees.
- The average face angle moved 3.3 degrees to a more closed position at impact
- The average spin axis moved 4.1 degrees towards a draw

A larger change in angle of attack was expected. This could be a result of test subject not swinging with loose wrists. The small change in angle of attack does not seem to account for the large changes in face angle and spin axis. The angle of attack was only recorded in about 50% of the shots made, and may therefore be underestimated. This may explain the small measured difference in angle of attack compared to the large change in face angle and spin axis.

Testing with Junior Athletes

The test program continued with students at IMG Golf Academy. A higher consistency was achieved from these young ambitious golfers who play golf every day. The lack of data from the Trackman with regard to Attack Angle, especially for the shorter clubs, remains a problem.

Further Testing

A lesson learned from the testing is that in order to obtain quality data, testing should be carried out with proficient golfers able to deliver a repeatable swing. Typically scratch handicap golfers give good results. Subjects need to be instructed to swing with loose wrists and practice this well synchronized swing before the actual testing commences.

Conclusion

The BioMatch method of matching golf clubs brings some much-needed science to the game of golf. For five centuries, the golf industry and golfers have attempted to find a method of matching golf clubs within a set. The industry seems to have given up on this, and many are relying on the Swingweight method as it may be considered better than nothing. BioMatch is the first known method that takes the properties of the golfer into consideration, without which it is not possible to match a set of golf clubs in a scientifically sound manner. This is the main difference between BioMatch and all earlier attempts to match golf clubs. Initial testing looks promising. Feedbacks from early users are overwhelmingly positive.

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Appendix A

Table A 1

	Percentage Variation in Original MOIG of a typical 7-iron															
Variable	-5%	-4%	-3%	-2%	-1%	original	+1%	+2%	+3%	+4%	+5%	+6%	+8%	+10%	+15%	+20%
MOIG	2065	2087	2109	2131	2152	2174	2196	2217	2239	2261	2283	2304	2348	2391	2500	2609
Mass	408	411	416	420	424	428	433	437	441	446	450	454	463	471	493	514
BMI	0.506	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507	0.507

By varying the MOIG put into the BioMatch program for a club, the resulting optimum mass of the club is changing. However, the BMI index remains constant.

Appendix B

Mass plotted against MOIG of a Typical 7-Iron

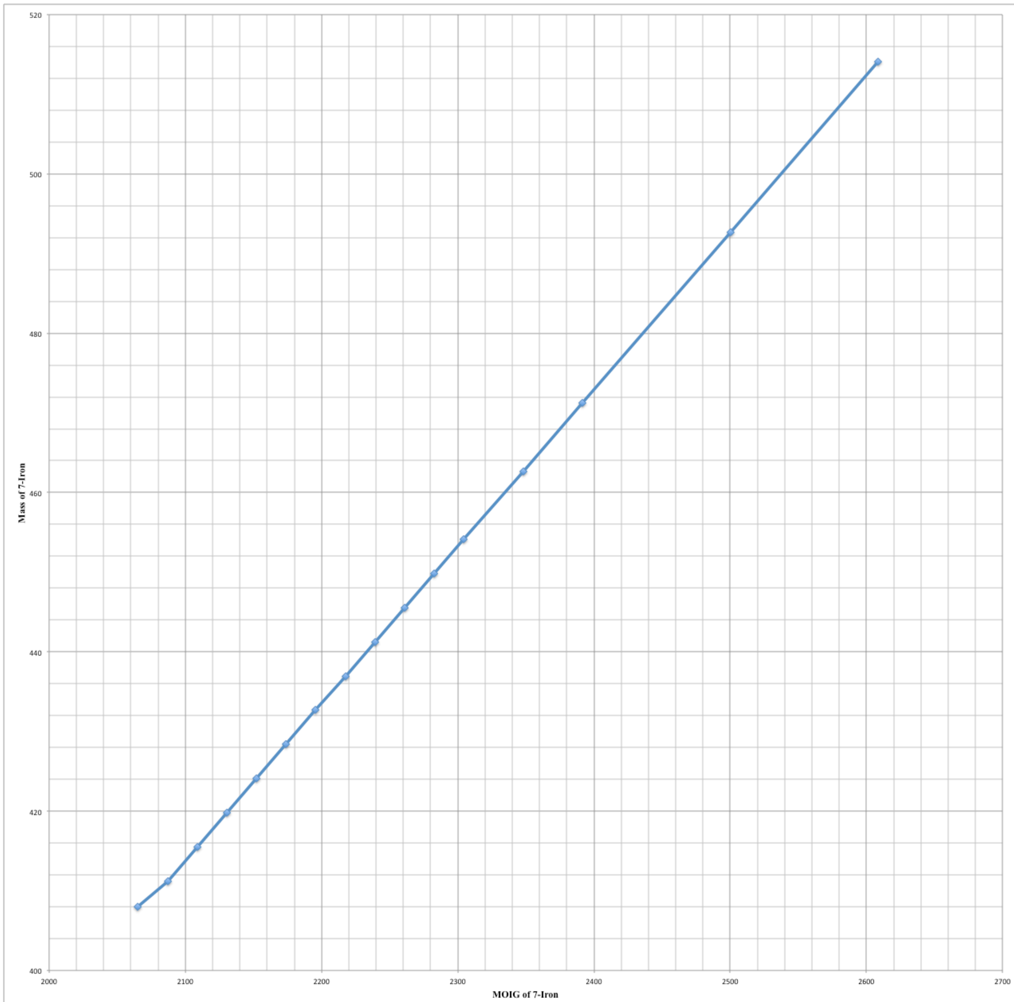


Figure B 1

Appendix C

March 12, 2018

GolfTest USA Summary Report on the BioMatch Club Matching System

This report is compiled based on the results of an independent test conducted on the BioMatch club matching system.

GolfTest USA had 13 golfers with handicaps ranging from 0 to 20 as test subjects. The testers had the results of shots hit at the Desert Hills golf range in Green Valley, Arizona. The subjects hit shots with their driver, 5 fairway wood, 6 iron and wedge. Each shot was recorded with a FlightScope Launch Monitor.

The inventor of BioMatch, Gisle Solhaug, then came to the GolfTest USA testing center. He had each tester meet with him so that he could evaluate their physical attributes and measure their set of clubs. He then entered all the information into the BioMatch algorithm on the Rational Golf website. Each club was then fitted with the correct weight at the grip end. The testers played a minimum of 5 rounds of golf over the next month. The testers recorded all their scores so their handicap could be compared to what it was before having the BioMatch system installed. After they had played their rounds of golf, they came back to the range and hit shots with the same clubs.

When all of the results were compared, it showed that the testers as a group improved their distance by an average of 3.5%. Their accuracy improved 2.9%. Their club head speed remained the same, showing no statistical difference. The improvement in distance and accuracy indicates that the testers were making more solid contact and hitting the sweet spot more consistently.

The average of all the testers' handicaps showed a decrease of 1.1 per round. It should be noted that all the test subjects are seasoned golfers that normally would not experience any improvement with time.

Based on the average of all the handicaps that was an improvement of 12% across all the testers.

After the test was completed the testers completed an online survey where they answered questions about how well they felt they did with the BioMatch system installed in their clubs.

Below are the responses from the testers when asked what their experience was with the BioMatch System. Almost all the responses are positive.

What was your experience playing with the BioMatch system?

01/21/2018	23210170	The concept is quite intriguing.
01/19/2018	23201900	Driver improved by 10 yards in distance.
01/18/2018	23194531	I didn't even think about it while playing.

01/17/2018	23190859	My wedge seemed to work better with more consistent hits. Wedge has been worse club in bag and now somewhat better.
01/17/2018	23185271	I liked the increased distance of the irons and fairway woods
01/17/2018	23183315	I didn't feel much difference
01/16/2018	23181003	Felt that it did cause all of the clubs to feel more similar. This was most noticeable in clubs from different manufacturers such as driver and 7 fairway wood and 3 mismatched wedges. I did not notice any difference before or after BioMatch in the factory matched irons.
01/16/2018	23180935	Very little difference between clubs. They all felt the same when swinging.
01/16/2018	23180832	Clubs felt more balanced, But it did not much difference in my overall game
01/16/2018	23180348	I felt the club head release nicely with the irons and really liked the bounce/turf reaction with the irons
01/16/2018	23180124	Better tempo
01/16/2018	23180067	Increased confidence. But also paying more attention to my stance, swing, etc. So maybe that helped as much as the BioMatch itself.
01/16/2018	23179800	No adjustment needed

Based on the results it is concluded by GolfTest USA that it is apparent that the BioMatch System will help most golfers improve the consistency and tempo of their golf swing resulting in a better golf game.

GolfTest USA feels the cost of having the BioMatch System installed on a set of clubs is worth the investment and will help most golfers get a better understanding of what goes into the dynamics of a golf swing and the steps that can be taken to improving it.

GolfTest USA has determined based the results of the test that the BioMatch System qualifies to be awarded the coveted "GolfTest USA Seal of Excellence." A product that has been awarded The "GolfTest USA Seal of Excellence" tells golfers they can feel confident that it is a product of quality, value, and performance.

Further information on the BioMatch matching system is available on www.rational-golf.com.

Yours Sincerely

Wayne Williams
CEO
GolfTest USA

Appendix D

Comments to Test by GolfTest USA

Quality of Test

The test was carried out in an outdoor environment using driving range balls. The driving range balls would have deteriorated further in the 6-week interval between the first test, without BioMatch, and the second test, with BioMatch. In particular one day of testing with BioMatch there was strong headwind coming in slightly from the left.

A flight scope was used to measure the shots. This instrument did not give consistent measurements for the angle of attack. Most shots did not register an angle of attack.

The test procedure provided was not followed in that the same club was hit five times in a row, rather than hitting clubs in a predetermined order. This test will, therefore, not distinguish the BioMatch clubs from the ordinary clubs when it comes to dispersion.

All the test subjects, except for one, were retired people. The average age was about 75 years.

Conclusion Provided by GolfTest USA

Comparing the results before and after adapting BioMatch, it showed that the testers as a group improved their distance by an average of 3.5%. Their accuracy improved 2.9%. Their club head speed remained the same, showing no statistical difference. The improvement in distance and accuracy indicates that the testers were making more solid contact and hitting the sweet spot more consistently.

The average of all the testers' handicaps showed a decrease of 1.1. It should be noted that all the test subjects are seasoned golfers that normally would not experience any improvement with time.

Analyzing the FlightScope Numbers

BioMatch weights will affect the angle of attack. According to the theory, the more weight added to the grip end of the club, the slower the hands will move during the downswing. This will result in a larger angle of attack. That is, the golfer will be hitting less down on the ball. This will give a higher launch angle and thereby higher ball flight.

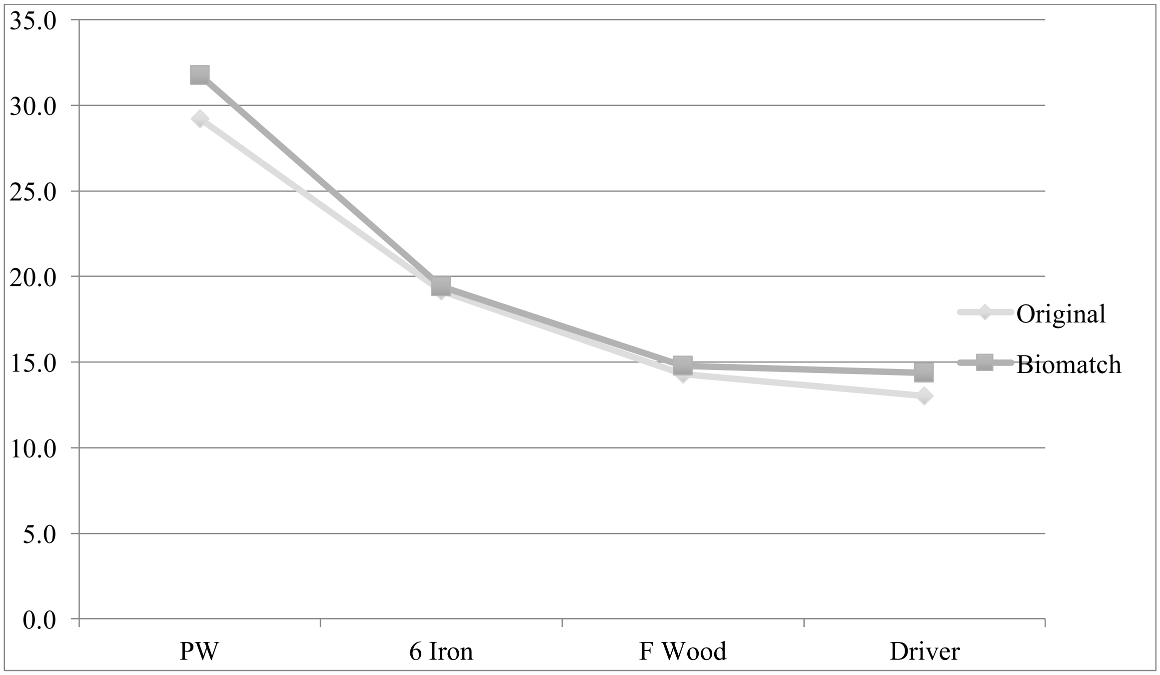
Due to the limited quality of the test, there are very few conclusions that can be made. Results are in general inconsistent and do not provide scientific proof of the BioMatch advantages over matching by Swingweight.

The launch angle is however consistently higher with the BioMatch clubs, throughout the sets. The launch angle increased on average by 6%. Which again suggest that the angle of attack is increased (less negative) as the BioMatch method promotes. The maximum ball flight height increased on average by 10%.

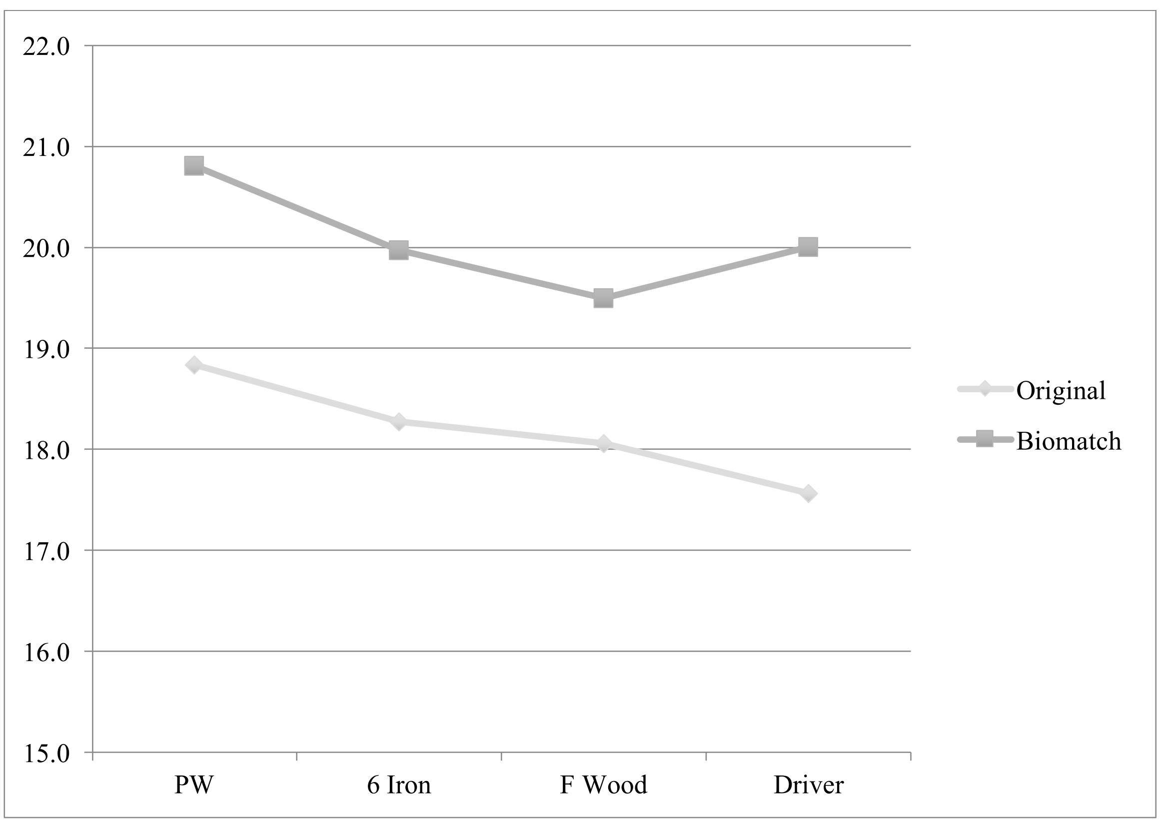
The test thereby indicates that increasing the overall weight of a club, while not altering the MOI substantially, will slow down the hands and the angle of attack increases. This shows that the hand position at impact is influenced by the overall weight of the clubs as described by the BioMatch method of matching golf clubs.

Further, more scientific, testing needs to be carried out to confirm the advantages of the BioMatch method.

Average Launch Angle



Maximum Height of Ball Flight



Conclusion

The test carried out by GolfTest USA indicates that the BioMatch method of matching golf clubs at least has some merits. Adding weight to the grip end of the club is proven to slow down the hands. It thereby makes sense that by adding the correct amount of weight to each club in a set the golfer will be able to apply the same consistent swing to all the clubs in the set. In other words, the weight of each club can be optimized so that the golfer can apply a consistent torque with his shoulders and the hands will automatically be positioned in the appropriate position.

It should be noted that most golfers would adjust their swing to suit the BioMatch clubs. This did not seem to happen in this test. Most likely due to the age of the subjects. Typically the golfer´s subconscious mind will feel the added mass and make adjustments in the swing. Thereby not altering the angle of attack significantly, but rather realize that the same consistent swing can be applied to all the clubs.