COMMON FIXED POINTS BY TWO STEP ITERATIVE SCHEME FOR ASYMPTOTICALLY NONEXPANSIVE MAPPINGS

M. R. Yadav

School of Studies in Mathematics, Pt. Ravishankar Shukla University, Raipur, Chhattisgarh (India)-492010

Abstract. In this paper, we introduce an iteration scheme for approximating common fixed points of two asymptotically nonexpansive mappings in the framework of a uniformly convex Banach spaces and established weak and strong convergence results for common fixed points of asymptotically nonexpansive mappings. The results obtained in this paper are generalizations of Khan [9]. Our result also illustrated with help of an example.

1. Introduction

Let $E$ be a real Banach space, $K$ be a nonempty, closed and convex subset of $E$. Throughout this paper, $\mathbb{N}$ denotes the set of all positive integers and $F(T) := \{ x : Tx = x \}$ is the set of fixed point of $T$. A mapping $T : K \to K$ is said to be asymptotically nonexpansive if for a sequence $\{k_n\} \subset [1, \infty)$ with $\lim_{n \to \infty} k_n = 1$, if $\| T^n x - T^n y \| \leq k_n \| x - y \|$, for all $x, y \in K$ and for all $n \in \mathbb{N}$. This class of asymptotically nonexpansive mappings was introduced by Goebel and Kirk [7] in 1972. They proved that if $K$ is a nonempty bounded closed convex subset of a uniformly convex Banach space $E$, then every asymptotically nonexpansive self-mapping $T$ of $K$ has a fixed point. The fixed point iteration process for asymptotically nonexpansive mapping in Banach spaces including Mann and Ishikawa iterations processes have been studied extensively by many authors; see ([1]-[20]).

The Picard and Mann [21] introduced the following iteration process: $T : K \to K$ are defined by

$$\begin{align*}
x_1 &= x_0 \in K, \\
x_{n+1} &= T^n x_n
\end{align*}$$

(1)

for all $n \in \mathbb{N}$ is called the Picard iteration process and

$$\begin{align*}
x_1 &= x_0 \in K, \\
x_{n+1} &= (1 - \alpha_n)x_n + \alpha_n T^n x_n, n \in \mathbb{N},
\end{align*}$$

(2)

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Email address: yadavmryadav@gmail.com (M. R. Yadav)
where \(\{\alpha_n\}\) is in \((0, 1)\) is called the Mann iteration process.

Recently Khan [9] defined two-step iteration procedure as:

\[
\begin{aligned}
  x_1 &= x_0 \in K, \\
  x_{n+1} &= T^n[(1 - \beta_n)x_n + \beta_nT^x_n], n \in \mathbb{N},
\end{aligned}
\]

where \(\{\beta_n\}\) in \((0, 1)\).

The aim of this paper is to establish a new two-step iterative process and compute the common fixed points for two asymptotically nonexpansive mappings. Let \(S, T : K \rightarrow K\) be two asymptotically nonexpansive mappings. Then, our process read as follows:

\[
\begin{aligned}
  x_1 &= x_0 \in K, \\
  x_{n+1} &= T^n[(1 - \beta_n)S^n x_n + \alpha_n T^x_n], n \geq 1,
\end{aligned}
\]

where \(\{\beta_n\}\) in \([0, 1]\). However, iteration process (4) reduce to iteration process (3) when \(S = I\), that is, the identity mapping.

Our purpose in the rest of the paper is to use the scheme (4) to prove weak and strong convergence results for approximating common fixed points of two asymptotically nonexpansive mappings.

2. Preliminaries

Let \(X = \{x \in E : \|x\| = 1\}\) and \(E^*\) be the dual of \(E\). The space \(E\) has:

(i) Gâteaux differentiable norm if

\[
\lim_{t \to 0} \frac{\|x + ty\| - \|x\|}{t},
\]

exists for each \(x, y \in K\);

(ii) Fréchet differentiable norm (see e.g. [23]) for each \(x\) in \(S\), the above limit exists and is attained uniformly for \(y\) in \(S\) and in this case, it is also well-known that

\[
\langle h, f(x) \rangle + \frac{1}{2}\|h\|^2 \leq \frac{1}{2}\|x + h\|^2 \leq \langle h, f(x) \rangle + \frac{1}{2}\|h\|^2 + b(\|h\|)
\]

for all \(x, h \in E\), where \(f\) is the Fréchet derivative of the function \(\frac{1}{2}\|\cdot\|^2\) at \(x \in E\), \(\langle \cdot, \cdot \rangle\) is the dual pairing between \(E\) and \(E^*\), and \(b\) is an increasing function defined on \([0, \infty)\) such that \(\lim_{t \to 0} \frac{b(t)}{t} = 0\);

(iii) Opial’s condition [24] if for any sequence \(\{x_n\}\) in \(E\), \(x_n \rightharpoonup x\) implies that

\[
\limsup_{n \to \infty}\|x_n - x\| < \limsup_{n \to \infty}\|x_n - y\|
\]

for all \(y \in E\) with \(y \neq x\).

Let us recall the following definitions.

**Definition 2.1.** Let \(K\) be a nonempty, closed and convex subset of Banach space \(E\) and \(T : K \rightarrow K\) be a mapping. Then, \(T\) is said to be asymptotically quasi-nonexpansive if there exists a sequence \(\{k_n\}_0^\infty\) in \([1, +\infty)\) with \(\lim_{n \to +\infty} k_n = 1\) such that

\[
\|Tx_n - p\| \leq k_n\|x - p\|
\]

for all \(x \in K\) and for all \(q \in F(T)\) (\(F(T)\) denotes the set of fixed points of \(T\)) and \(n \geq 1\).

**Definition 2.2.** [11]. Let \(E\) be a Banach space, \(K\) be a nonempty, closed and convex subset of Banach space \(E\), and \(T : K \rightarrow K\) be a nonexpansive mapping. Then \(I - T\) is said to be demi-closed at 0, if \(x_n \rightarrow x\) (converges weakly) and \(x_n - Tx_n \rightarrow 0\) (converges strongly), then it is implies that \(x \in K\) and \(Tx = x\).
Definition 2.3. [6]. Let two mappings $S, T : K \rightarrow K$, where $K$ is a subset of a normed space $E$, said to be satisfy condition (A') if there exists a nondecreasing function $f : [0, \infty) \rightarrow [0, \infty)$ with $f(0) = 0$, $f(r) > 0$ for all $r \in (0, \infty)$ such that either $\|x - Sx\| \geq f(d(x, F))$ or $\|x - Tx\| \geq f(d(x, F))$ for all $x \in K$ where $d(x, F) = \inf\{\|x - p\| : p \in F = F(S) \cap F(T)\}$.

Now, we state the following useful lemma to prove our main results.

Lemma 2.4. [25]: If $(r_n), \{t_n\}$ are two sequences of nonnegative real numbers such that $r_{n+1} \leq (1 + t_n)r_n, n \geq 1$ and $\sum_{n=1}^{\infty} t_n < \infty$, then $\lim r_n$ exists.

Lemma 2.5. [14]: Let $E$ be a uniformly convex Banach space and $0 < p \leq t_n \leq q < 1$ for all $n \in \mathbb{N}$. Let $\{x_n\}$ and $\{y_n\}$ be two sequences of $E$ such that $\limsup_{n \rightarrow \infty} \|x_n\| \leq r, \limsup_{n \rightarrow \infty} \|y_n\| \leq r$ and $\lim_{n \rightarrow \infty} \|(1 - t_n)x_n + t_n y_n\| = r$ hold for some $r \geq 0$. Then $\lim_{n \rightarrow \infty} \|x_n - y_n\| = 0$.

3. Convergence Results

In this section, we prove weak and strong convergence theorems for two asymptotically nonexpansive mappings in the frame work of a uniformly convex Banach spaces.

Theorem 3.1. Let $K$ be a nonempty, closed and convex subset of a uniformly convex Banach space $E$. Let $S, T : K \rightarrow K$ be two asymptotically nonexpansive mappings with $F(S) \cap F(T) \neq \phi$ and a sequence $\{k_n\}$ of real numbers with $k_n \geq 1$ and $\sum_{n=1}^{\infty} (k_n^2 - 1) < \infty$. Let $\{x_n\}$ be the sequence defined by (4), where $\beta_n$ is a sequence in $[\epsilon, 1 - \epsilon]$ for some $\epsilon \in (0, 1)$ satisfying:

$$
\|x_n - T^n x_n\| \leq \lambda \|S^n x_n - T^n x_n\|, 
$$

(6)

for all $x, y \in K$, where $\lambda > 1$, then

$$
\lim_{n \rightarrow \infty} \|Sx_n - x_n\| = \lim_{n \rightarrow \infty} \|Tx_n - x_n\| = 0 .
$$

Proof. Let $p \in F(S) \cap F(T)$ and $F(S) \cap F(T) \neq \phi$. Put, for simplicity, $y_n = (1 - \beta_n)S^n x_n + \beta_n T^n x_n$. From (4), we have

$$
\|x_{n+1} - p\| = \|T^n y_n - p\|
\leq k_n \|y_n - p\|, 
$$

(7)

and,

$$
\|y_n - p\| = \|(1 - \beta_n)S^n x_n + \beta_n T^n x_n - p\|
\leq (1 - \beta_n)\|S^n x_n - p\| + \beta_n \|T^n x_n - p\|
\leq (1 - \beta_n)k_n \|x_n - p\| + \beta_n k_n \|y_n - p\|
\leq k_n \|x_n - p\|. 
$$

(8)

From (7) and (8), we have

$$
\|x_{n+1} - p\| \leq k_n^2 \|x_n - p\|
\leq \left(1 + (k_n^2 - 1)\|x_n - p\| \right). 
$$

Hence by using Lemma 2.4, $\lim_{n \rightarrow \infty} \|x_n - q\|$ exists. Let $\lim_{n \rightarrow \infty} \|x_n - p\| = c$ and suppose that $c > 0$. Now, from (8), we have

$$
\|y_n - p\| \leq \limsup_{n \rightarrow \infty} \|x_n - p\| \leq c, 
$$

(9)
Note that,
\[ \| y_n - p \| = \| T^n x_n - p \| \leq k_n \| x_n - p \| \leq c. \] (10)

Combining the estimates in (9) and (10), we have
\[ \| y_n - p \| = c. \] (11)

Next, consider
\[ c = \| y_n - p \| = \| (1 - \beta_n) S^n x_n + \beta_n T^n x_n - p \| \]
\[ \leq (1 - \beta_n) \| S^n x_n - p \| + \beta_n \| T^n x_n - p \|. \]

Applying Lemma 2.5, we have
\[ \lim_{n \to \infty} \| S^n x_n - T^n x_n \| = 0. \] (12)

Using (6) and (12), it follows then that
\[ \| S^n x_n - x_n \| = \| S^n x_n - T^n x_n \| + \| T^n x_n - x_n \| \]
\[ \leq \| S^n x_n - T^n x_n \| + \lambda \| S^n x_n - T^n x_n \| \]
\[ \Rightarrow (1 + \lambda) \| S^n x_n - T^n x_n \| \Rightarrow 0 \text{ as } n \to \infty. \]

Taking limsup on both sides of the above inequality, we obtain
\[ \lim_{n \to \infty} \| S^n x_n - x_n \| = 0. \]

Now, note that
\[ \| T^n x_n - x_n \| \leq \| T^n x_n - S^n x_n \| + \| S^n x_n - x_n \| \]
\[ \Rightarrow 0 \text{ as } n \to \infty, \]

which implies that
\[ \lim_{n \to \infty} \| T^n x_n - x_n \| = 0. \]

Now, by definition of \( \{ x_n \} \), we have
\[ \| x_{n+1} - T^n x_n \| \leq k_n \| S^n x_n - T^n x_n \|. \]

Taking limit as \( n \to \infty \) in both sides of the above inequality, we obtain
\[ \lim_{n \to \infty} \| x_{n+1} - T^n x_n \| = 0. \] (13)

Again note that, \( \| x_{n+1} - S^n x_n \| \leq \| x_{n+1} - T^n x_n \| + \| T^n x_n - S^n x_n \|. \)

Using (12) and (13), we obtain
\[ \lim_{n \to \infty} \| x_{n+1} - S^n x_n \| = 0. \] (14)

Also, \( \| x_{n+1} - x_n \| \leq \| x_{n+1} - T^n x_n \| + \| T^n x_n - x_n \| \), we get
\[ \lim_{n \to \infty} \| x_{n+1} - x_n \| = 0, \] (15)
and
\[ \|x_{n+1} - Sx_n\| \leq \|x_{n+1} - S^{n+1}x_{n+1}\| + \|S^{n+1}x_{n+1} - S^{n}x_{n}\| \]
\[ \leq \|x_{n+1} - S^{n+1}x_{n+1}\| + k_n\|x_{n+1} - x_n\| \]
\[ + k_n\|S^n x_n - x_n\|, \]

It follows from (14) and (15), we have
\[ \lim_{n \to \infty} \|x_n - Sx_n\| = 0. \]

Similarly, we may show that
\[ \lim_{n \to \infty} \|x_n - Tx_n\| = 0. \]

This proof is completed. \(\square\)

**Example 3.2.** Let \(E\) be the real line with the usual norm \(|.|\) and suppose \(K = [0,1]\). Define \(S,T : K \to K\) by
\[ Tx = \frac{2 - x}{2} \]
and
\[ Sy = \frac{y + 2}{4} \]
for all \(x, y \in K\). Obviously both \(S\) and \(T\) are asymptotically nonexpansive with the common fixed point \(\frac{2}{3}\) for all \(x, y \in K\). Now we check that our condition \(\|x - Sy\| \leq \lambda\|Tx - Sx\|\) for all \(x, y \in K\) is true. If \(x, y \in [0,1]\) and \(\lambda > 1\), then
\[ |x - Sy| = |x - \left(\frac{y + 2}{4}\right)| \]
\[ = \left|\frac{4x - y - 2}{4}\right|, \]
and
\[ |Tx - Sy| = \left|\frac{2 - x}{2} - \frac{y + 2}{4}\right| \]
\[ = \left|\frac{2x + y - 2}{4}\right|. \]

It is clear that \(\left|\frac{4x - y - 2}{4}\right| \leq \lambda\left|\frac{2x + y - 2}{4}\right|\), where \(\lambda > 1\), so \(|x - Sy| \leq \lambda\|Tx - Sx\|\) exists, for all \(x, y \in K\). Now, we check that \(S\) and \(T\) are quasi-nonexpansive type mappings. In fact, if \(x \in [0,1]\) and \(p = 0 \in [0,1]\), then
\[ |Tx - p| = \left|\frac{2 - x}{2} - 0\right| = \left|\frac{2 - x}{2}\right| \]
\[ = \left|\frac{2 - x}{2}\right| \leq |x| = |x - 0| = |x - p|, \]
that is
\[ |Tx - p| \leq |x - p|. \]

Similarly, we can prove that
\[ |Sx - p| \leq |x - p|. \]
So that \(S\) and \(T\) are quasi-nonexpansive type mappings.
Lemma 3.3. Let $K$ be a nonempty, closed and convex subset of a uniformly convex Banach space $E$. Let $\{x_n\}$ be the sequence defined in Theorem 3.4 with $F \neq \emptyset$. Then, for any $p_1, p_2 \in F$, $\lim_{n \to \infty} \langle x_n, (p_1 - p_2) \rangle$ exist, in particular, $(p - q, (p_1 - p_2)) = 0$ for all $p, q \in \omega_w(x_n)$.

Proof. Take $x = p_1 - p_2$, with $p_1 \neq p_2$ and $h = t(x_n - p_1)$ in the inequality (5) to get:

$$\frac{1}{2}\|p_1 - p_2\|^2 + t(x_n - p_1, (p_1 - p_2)) \leq \frac{1}{2}\|tx_n + (1-t)p_1 - p_2\|^2$$

$$\leq \frac{1}{2}\|p_1 - p_2\|^2 + t(x_n - p_1, (p_1 - p_2)) + b(t\|x_n - p_1\|).$$

As $\sup_{n \geq 1} \|x_n - p_1\| \leq M'$ for some $M' > 0$, it follows that

$$\frac{1}{2}\|p_1 - p_2\|^2 + t \limsup_{n \to \infty} (x_n - p_1, (p_1 - p_2)) \leq \frac{1}{2}\|tx_n + (1-t)p_1 - p_2\|^2$$

$$\leq \frac{1}{2}\|p_1 - p_2\|^2 + b(M')t \liminf_{n \to \infty} (x_n - p_1, (p_1 - p_2)).$$

That is,

$$\limsup_{n \to \infty} (x_n - p_1, (p_1 - p_2)) \leq \liminf_{n \to \infty} (x_n - p_1, (p_1 - p_2)) + \frac{b(M')}{tM'}M'.$$

If $t \to 0$, then $\lim_{n \to \infty} (x_n - p_1, (p_1 - p_2))$ exists for all $p_1, p_2 \in F$, in particular, we get

$$\langle p - 1, (p_1 - p_2) \rangle = 0$$

for all $p, q \in \omega_w(x_n)$. \qed

Theorem 3.4. Let $E$ be a uniformly convex Banach space satisfying Opial condition and $K, T, S$ and $\{x_n\}$ be taken as Theorem 3.1. If $F(S) \cap F(T) \neq \emptyset$, $I - T$ and $I - S$ are demiclosed at zero, then $\{x_n\}$ converges weakly to a common fixed point of $S$ and $T$.

Proof. Let $p \in F(S) \cap F(T)$, then as proved in Theorem 3.1 $\lim_{n \to \infty} \|x_n - p\|$ exist. Since $E$ is uniformly convex Banach space. Thus there exists subsequences $\{x_{n_k}\} \subset \{x_n\}$ such that $\{x_{n_k}\}$ converges weakly to $z_1 \in K$. From Theorem 3.1, we have

$$\lim_{n \to \infty} \|Tx_{n_k} - x_{n_k}\| = 0,$$

and

$$\lim_{n \to \infty} \|Sx_{n_k} - x_{n_k}\| = 0.$$

Since $I - T$ and $I - S$ are demiclosed at zero, therefore $Sz_1 = z_1$. Similarly $Tz_1 = z_1$. Finally, we prove that $\{x_{n_k}\}$ converges weakly to $z_1$. Let on contrary that there exists a subsequence $\{x_{n_k}\} \subset \{x_n\}$ and $\{x_{n_{j_k}}\} \subset \{x_n\}$ such that $\{x_{n_k}\}$ converges weakly to $z_2 \in K$ and $z_1 \neq z_2$. Again in the same way, we can prove that $z_2 \in F(S) \cap F(T)$. From Theorem 3.1 the limits $\lim_{n \to \infty} \|x_n - z_1\|$ and $\lim_{n \to \infty} \|x_n - z_2\|$ exist. Suppose that $z_1 \neq z_2$, then by the Opial’s condition, we get

$$\lim_{n \to \infty} \|x_n - z_1\| = \lim_{n \to \infty} \|x_{n_k} - z_1\| < \lim_{n \to \infty} \|x_n - z_2\|$$

$$= \lim_{n \to \infty} \|x_{n_{j_k}} - z_2\| = \lim_{n \to \infty} \|x_{n_{j_k}} - z_2\|$$

$$< \lim_{n \to \infty} \|x_{n_{j_k}} - z_1\| = \lim_{n \to \infty} \|x_n - z_1\|.$$
Theorem 3.5. Let $E$ be a Banach space and $K, S, T, F, \{x_n\}$ be as in Lemma 3.1. If $F(T) \neq \phi$, then $\{x_n\}$ converges strongly to a common fixed point of $T$ if and only if $\liminf_{n \to \infty} d(x_n, F) = 0$ where $d(x, F) = \inf\{\|x - p\| : p \in F\}$.

Proof. Necessity is obvious. Conversely, suppose that $\liminf_{n \to \infty} d(x_n, F) = 0$. As in the proof of Lemma 3.1, we have

$$\|x_{n+1} - p\| \leq k_n\|x_n - p\|.$$ 

This gives

$$\|x_{n+1} - F\| \leq k_n\|x_n - F\|.$$ 

So that $\lim d(x_n, F)$ exists. But by hypothesis $\liminf_{n \to \infty} d(x_n, F)$, so we must have $\lim d(x_n, F) = 0$.

Next, we show that $\{x_n\}$ is a Cauchy sequence in $K$. Suppose $\varepsilon > 0$ be given. Since $\lim d(x_n, F) = 0$, there exists $n_0$ in $N$ such that for all $n \geq n_0$, we get $d(x_n, F) < \frac{\varepsilon}{2}$. In particular, $\inf\{\|x_n - p\| : p \in F\} < \frac{\varepsilon}{2}$. There must exist $p' \in F$ such that $\|x_{n_0} - p'\| < \frac{\varepsilon}{2}$. Now for $n, m \geq n_0$, we have

$$\|x_{n+m} - x_n\| \leq \|x_{n+m} - p'\| + \|p' - x_n\|$$

$$\leq 2\|p' - x_n\|$$

$$\leq \frac{\varepsilon}{2} = \varepsilon.$$ 

Hence $\{x_n\}$ is a Cauchy sequence in a closed subset $K$ of a Banach space $E$, therefore it must converge in $K$. Suppose $\lim x_n = q$. Now $\lim d(x_n, F) = 0$ gives that $d(x, F) = 0$. It is well-known that $F$ is closed and so $q \in F$. □

Using Theorem 3.5, we obtain a strong convergence theorem of the iteration scheme (4) under the condition (A') as below:

Theorem 3.6. Let $E$ be a uniformly convex Banach space and $K, S, T, F, \{x_n\}$ be as in Theorem 3.1. Let $S, T$ satisfy the condition (A') and $F \neq \phi$. Then $\{x_n\}$ converges strongly to a point of $F$.

Proof. We proved in Theorem 3.1, i.e.

$$\lim_{n \to \infty} ||Sx_n - x_n|| = 0 = \lim_{n \to \infty} ||Tx_n - x_n||$$

Then from the definition of condition (A'), we obtain

$$\lim_{n \to \infty} f(d(x_n, F)) \leq \lim_{n \to \infty} ||Tx_n - x_n|| = 0$$

or

$$\lim_{n \to \infty} f(d(x_n, F)) \leq \lim_{n \to \infty} ||Sx_n - x_n|| = 0.$$ 

In above cases, we get

$$\lim_{n \to \infty} f(d(x_n, F)) = 0.$$ 

But $f : [0, \infty) \to [0, \infty)$ is a nondecreasing function satisfying $f(0) = 0, f(r) > 0$ for all $r \in (0, \infty)$, so that we get

$$\lim_{n \to \infty} d(x_n, F) = 0.$$ 

□
All the conditions of Theorem 3.5 are satisfied, therefore by its conclusion \( \{x_n\} \) converges strongly to a fixed point of \( F \).

We now state two strong convergence theorems. The mapping \( T : K \to K \) with \( F(T) \neq \emptyset \) is said to satisfy condition (A) [22] if there is a nondecreasing function \( f : [0, \infty) \to [0, \infty) \) with \( f(0) = 0 \) and \( f(r) > 0 \) for all \( r \in (0, \infty) \) such that for all \( x \in K \), \( \|x - T(K)\| \geq d(x, F(T)) \).

**Theorem 3.7.** Let \( E \) be a uniformly convex Banach space and \( K \) a nonempty, closed, convex subset of \( E \) which is also a asymptotically nonexpansive retract of \( E \). Let \( T : K \to K \) be a asymptotically nonexpansive mapping with \( F(T) \neq \emptyset \). Let \( \{\beta_n\} \) be sequences in \( [c, 1 - c] \) for some \( c \in (0, 1) \). From arbitrary \( x_1 \in K \), define the sequence \( \{x_n\} \) by the recursion (3). Suppose \( T \) satisfies condition (A). Then \( \{x_n\} \) converges strongly to some fixed point of \( T \).

**Theorem 3.8.** Let \( E \) be a uniformly convex Banach space and \( K \) a nonempty, closed, convex subset of \( E \) which is also a asymptotically nonexpansive retract of \( E \). Let \( T : K \to K \) be a asymptotically nonexpansive mapping with \( F(T) \neq \emptyset \). Let \( \{\alpha_n\} \) be sequences in \( [c, 1 - c] \) for some \( c \in (0, 1) \). From arbitrary \( x_1 \in K \), define the sequence \( \{x_n\} \) by the recursion (3). Suppose that \( T(K) \) is contained in a compact subset of \( E \). Then \( \{x_n\} \) converges strongly to some fixed point of \( T \).

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