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## A new iterative algorithm for total asymptotically nonexpansive mapping in CAT(0) spaces

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### Abstract

In this paper, We demonstrate various convergence theorems of a new iteration procedure for total asymptotically nonexpansive mapping in the context of CAT(0) spaces, as well as numerical examples to compare the rate of convergence of our iteration process with several existing iteration processes. Our result, generalizes the result of Thakur et al. (29), Izhhar et al. (30) and many more in this direction.

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### 1 Introduction

Once the existence of a solution for an operator equation is confirmed, such a solution cannot be derived analytically in many circumstances. To overcome such situations, one must approximate the value of the answer. To accomplish this, we first arrange the operator equation in the form of a fixed point equation, then apply the most appropriate iterative algorithm to the fixed point equation, then the limit of the sequence generated by the most appropriate iterative algorithm. In actuality, the desired fixed point value for the fixed point equation and the operator equation solution. In this direction in 1920, Banach fixed point theorem enforced and suggest a simple iterative algorithm  $\check{x}_{m+1} = S\check{x}_m$  (Picard iterative algorithm) for contraction mapping, but it fails to converge the fixed point for nonexpansive mappings, to illustrated,  $S: [0, 1] \rightarrow [0, 1]$  defined by  $S\check{x} = 1 - \check{x}$ , with initial choice  $\check{x}_0 \neq 1/2$ , Picard iterative algorithm is not convergent. Then natural question arise:

**Question:** Does there exist an iterative algorithm which converges for nonexpansive mapping in suitable spaces ?

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The affirmative answer was given by Mann(21), Ishikawa(15), Noor(22) not only for nonexpansive mapping but also for more general than nonexpansive mapping in various topological space.

Naturally the various researcher attract in this direction, if the iterative algorithm exists for approximation fixed point, which converges to faster, toward fixed point.

Affirmative approach was given by Agarwal et al.(1) in 2007, by introduce S-iteration process defined as follows:

Let  $\Theta$  be a convex subset of normed space  $X$  and a non-linear mapping  $S$  of  $\Theta$  into itself, the sequence  $\{\varsigma_m\}$  in  $\Theta$  defined by

$$\begin{aligned} \varsigma_1 &\in \Theta \\ \varsigma_{m+1} &= (1 - \alpha_m)S\varsigma_m + \alpha_m S\nu_m \\ \nu_m &= (1 - \beta_m)\varsigma_m + \beta_m S\varsigma_m \quad \forall m \geq 1, \end{aligned}$$

where  $\{\varsigma_m\}$  is real sequence in  $(0,1)$ .

After the development of S- iteration process,numerous researchers developed iteration processes, including Thakur et al. (29), modified Picard S-hybrid iteration (20), modified Picard Mann hybrid (29).

In the last decades, so many researchers attract to approximate fixed point in CAT(0) space (see (10),(13)). Now we discuss about CAT(0) space and there properties.

A CAT(0) space is one in which all geodesic triangles of acceptable size satisfy the following CAT(0) comparison axiom.

Let  $\Delta$  be a geodesic triangle in  $\Theta$ , and let  $\bar{\Delta} \subset \mathbb{R}^2$  be comparison triangle for  $\Delta$ . Then  $\Delta$  is said to satisfy the CAT(0) inequality if for all  $\check{x}, \check{y} \in \Delta$  and all comparison points  $\check{\bar{x}}, \check{\bar{y}} \in \bar{\Delta}$ ,

$$\varphi(\check{x}, \check{y}) \leq \varphi_{\mathbb{R}^2}(\check{\bar{x}}, \check{\bar{y}}).$$

If  $\check{x}, \check{y}_1, \check{y}_2$  are points of a CAT(0) space and  $y_0$  is the midpoint of the segment  $[\check{y}_1, \check{y}_2]$  which we will denote by  $(\check{y}_1 \oplus \check{y}_2)/2$ , then the CAT(0) inequality implies

$$\varphi^2(\check{x}, \frac{\check{y}_1 \oplus \check{y}_2}{2}) \leq \frac{1}{2}\varphi^2(\check{x}, \check{y}_1) + \frac{1}{2}\varphi^2(\check{x}, \check{y}_2) - \frac{1}{4}\varphi^2(\check{y}_1, \check{y}_2).$$

this inequality is the (CN) inequality of Bruhat and Tits (5).

Let  $\Theta$  be a nonempty closed subset of a CAT(0) space,  $M$  and  $S$  be a self map defined on  $\Theta$ . Then  $S$  is said to be:

1. nonexpansive if

$$\varphi(S^m \varsigma, S^m \nu) \leq \varphi(\varsigma, \nu), \forall \varsigma, \nu \in \Theta;$$

2. asymptotically nonexpansive if  $\exists$  a sequence  $\{\xi_m\}$  in  $[1, \infty)$  with  $\lim_{m \rightarrow \infty} \xi_m = 1$  such that

$$\varphi(S^m \varsigma, S^m \nu) \leq \xi_m \varphi(\varsigma, \nu), \forall \varsigma, \nu \in \Theta \text{ and } \forall m \geq 1;$$

3. uniformly  $L$ -Lipschitzian if  $\exists$  a constant  $L > 0$  such that

$$\varphi(S^m \varsigma, S^m \nu) \leq L \varphi(\varsigma, \nu), \forall \varsigma, \nu \in \Theta \text{ and } \forall m \geq 1;$$

Goebel and Kirk (13) presented the class of asymptotically nonexpansive mappings as a generalization of the class of nonexpansive maps in 1972. They established that if  $\Theta$  is a nonempty closed convex bounded subset of a real uniformly convex Banach space and  $S$  is an asymptotically nonexpansive self-mapping of  $\Theta$ ,  $S$  has a fixed point. Following that, numerous researchers were inclined to phrase the approximating the fixed point for asymptotically nonexpansive mapping via, Mann (21), Ishikawa (15), and Noor (22) in various topological spaces (see in (3),(12),(17),(23)).

Bruck et al. (4), proposed asymptotically nonexpansive intermediate sense mappings.

**Definition 1.1.** If an operator  $s$  is continuous and the following condition holds, it is said to be asymptotically nonexpansive in the intermediate sense:

$$\lim_{m \rightarrow \infty} \sup_{\zeta, \nu \in \Theta} (\wp(S^m \zeta, S^m \nu) - \wp(\zeta, \nu)). \tag{1.1}$$

Observe that if

$$\check{a}_n = \sup_{\zeta, \nu \in \Theta} (\wp(S^m \zeta, S^m \nu) - \wp(\zeta, \nu)). \tag{1.2}$$

then (1.1) reduces to the relation

$$\wp(S^m \zeta, S^m \nu) \leq \wp(\zeta, \nu) + \check{a}_n \quad \forall \zeta, \nu \in \Theta. \tag{1.3}$$

It is worth noting that the class of asymptotically nonexpansive maps is correctly included within the class of asymptotically nonexpansive mappings in the intermediate sense (see, e.g., (14)).

Alber et al. (2) initially established the concept of total asymptotically nonexpansive mappings in 2006 (see also (7),(8),(14),(20)) defined as follows.

**Definition 1.2.** A self mapping  $S$  on  $\Theta$  is called  $(\{\mu_m\}, \{\varkappa_m\}, \varphi)$  total asymptotically nonexpansive mapping if there exist nonnegative real sequences  $\{\mu_m\}$  and  $\{\varkappa_m\}$  with  $\mu_m \rightarrow 0, \varkappa_m \rightarrow 0$  as  $m \rightarrow \infty$  and a continuous strictly increasing function  $\varphi: [0, \infty) \rightarrow [0, \infty)$  with  $\varphi(0) = 0$  such that

$$\wp(S^m \zeta, S^m \nu) \leq \wp(\zeta, \nu) + \mu_m \varphi(\wp(\zeta, \nu)) + \varkappa_m. \tag{1.4}$$

$\forall \zeta, \nu \in \Theta$  and  $\forall m \geq 1$ .

**Remark.** If  $\phi(\lambda) = \lambda$ , then (1.4) takes the form

$$\wp(S^m \zeta, S^m \nu) \leq (1 + \mu_m) \wp(\zeta, \nu) + \varkappa_m. \tag{1.5}$$

**Remark.** In addition, if  $\varkappa_m = 0$  for all  $m \geq 1$ , then total asymptotically nonexpansive mappings coincide with asymptotically nonexpansive mappings.

**Remark.** If  $\mu_m = 0$  and  $\varkappa_m = 0$  for all  $m \geq 1$ , then we obtain from (1.4) the class of nonexpansive mappings.

In 2012, Chang et al. (6) demiclosedness principle for total asymptotically nonexpansive mapping in CAT(0) space and established strong and *Delta*-convergence theorem for Mann iteration process. As a result, other researchers established strong and *Delta*-convergence theorem for the same mapping through modified Ishikawa (24), S-iteration process (18), modified Picard S-hybrid iteration (20), modified Picard Mann hybrid (29) in CAT(0) spaces.

Recently, Izhar et al. (30) presented A modified iteration process  $\{\zeta_m\}$  and  $\{\nu_m\}$ , which is defined below:

$$\begin{aligned} \zeta_1 &\in \Theta \\ \omega_m &= S^m((1 - \alpha_m)\zeta_m \oplus \alpha_m S^m \zeta_m) \\ \nu_m &= S^m((1 - \beta_m)S^m \omega_m \oplus \beta_m S^m \omega_m) \\ \zeta_{m+1} &= S^m \nu_m \end{aligned} \tag{1.6}$$

for all  $m \geq 1$ , where  $\{\alpha_m\}$  and  $\{\beta_m\}$  are appropriate sequences in the interval (0,1) and They established various convergence theorems of the iterative scheme created sequence (1.6) to approximate the fixed point of total asymptotically nonexpansive mapping in CAT(0) spaces.

Motivated by above work, we introduce a new iteration process in CAT(0) space.

Let  $\Theta$  be a nonempty subset of CAT(0) space.  $S: \Theta \rightarrow \Theta$  be a total asymptotically nonexpansive mapping. Let  $\{e_m\}$  be sequence in  $\Theta$  define iteratively as follows:

$$e_1 \in \Theta$$

$$\begin{aligned}
 e_{m+1} &= S^m f_m \\
 f_m &= S^m [(1 - \alpha_m)g_m \oplus \alpha_m S^m g_m] \\
 g_m &= S^m [(1 - \beta_m)h_m \oplus \beta_m S^m h_m] \\
 h_m &= S^m [(1 - \gamma_m)e_m \oplus \gamma_m S^m e_m]
 \end{aligned}
 \tag{1.7}$$

for all  $m \geq 1$ , where  $\{\alpha_m\}, \{\beta_m\}$  and  $\{\gamma_m\}$  are appropriate sequences in the interval  $(0,1)$ . In this paper we prove various iterative sequence convergence theorems (1.7) for total asymptotically nonexpansive mapping in CAT(0) spaces, and we also show numerical examples to compare the rate of convergence of our iteration process with several existing iteration processes. Our result, generalize the result of Izhar et al.(30) and many more in this direction.

## 2 Preliminaries

This section contains some well-known concepts and results that will be referenced throughout the paper.

**Lemma 2.1.** ((10)) Let  $M$  be a CAT(0) space,  $\check{a}, \check{b}, \check{c} \in M$  and  $t \in [0, 1]$ . Then

$$\wp(t\check{a} \oplus (1-t)\check{b}, \check{c}) \leq t\wp(\check{a}, \check{c}) + (1-t)\wp(\check{b}, \check{c}).$$

Let  $\{\check{a}_m\}$  be a bounded sequence in  $M$ , complete CAT(0) spaces. For  $\check{a} \in M$  set:

$$r(\check{a}, \{\check{a}_m\}) = \lim_{m \rightarrow \infty} \sup \wp(\check{a}, \check{a}_m).$$

The asymptotic radius  $r(\{\check{a}_m\})$  is given by

$$r(\{\check{a}_m\}) = \inf\{r(\check{a}, \check{a}_m) : \check{a} \in M\}.$$

and the asymptotic center  $\mathcal{A}(\{\check{a}_m\})$  of  $\{\check{a}_m\}$  is defined as:

$$\mathcal{A}(\{\check{a}_m\}) = \{\check{a} \in M : r(\check{a}, \check{a}_m) = r(\{\check{a}_m\})\}.$$

$\mathcal{A}(\{\check{a}_m\})$  consists of exactly one point in CAT(0) spaces see ( (11), Proposition 7). A sequence  $\{\check{a}_m\}$  in  $M$  is said to  $\Delta$ -converges to  $\check{a} \in M$  if  $\check{a}$  is the unique asymptotic center for every subsequence  $\{\check{z}_m\}$  of  $\{\check{a}_m\}$ . In this case we write  $\Delta - \lim_{m \rightarrow \infty} \check{a}_m = \check{a}$  and read as  $\check{a}$  is the  $\Delta - limit$  of  $\{\check{a}_m\}$ .

**Lemma 2.2.** ((9)) Let  $M$  be a complete CAT(0) space and  $\{\check{a}_m\}$  be a bounded sequence in  $M$ . If  $\mathcal{A}(\{\check{a}_m\}) = \{\rho\}$ ,  $\{\check{z}_m\}$  is a subsequence of  $\{\check{a}_m\}$  such that  $\mathcal{A}(\{\check{z}_m\}) = \{\check{z}\}$  and  $\wp(\check{a}_m, \check{z})$  converges, then  $\rho = \check{z}$ .

Recall that according to Karapinar et al. (16), the fixed point existence theorem and the demiclosedness principle for mappings fulfil Definition 1.2 in CAT(0) spaces.

**Lemma 2.3.** ((16)) Suppose  $S: \Theta \rightarrow \Theta$  be a nonempty convex closed and bounded subset of  $M$ , a complete CAT(0) space. Let  $S$  be uniformly continuous and total asymptotically nonexpansive mapping. Then,  $S$  has a fixed point, and set of fixed points  $F(S)$  is convex and closed.

**Lemma 2.4.** ((16)) Suppose  $S: \Theta \rightarrow \Theta$  be a nonempty closed, convex subset of  $M$ , a complete CAT(0) space. Let  $S$  be a uniformly continuous and total asymptotically nonexpansive mapping. For every bounded sequence  $\{\check{z}_m\} \in \Theta$  such that,  $\lim_{m \rightarrow \infty} \wp(\check{a}_m, S\check{a}_m) = 0$  and  $\lim_{m \rightarrow \infty} \check{a}_m = q$  implies that  $Sq = q$ .

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**Lemma 2.5.** ((26)) Let  $M$  be a complete CAT(0) space and let  $\check{a} \in M$ . Suppose  $\{t_m\}$  is a sequence in  $[\check{b}, e]$  for some  $\check{b}, e \in (0, 1)$  and  $\{\check{a}_m\}, \{\check{b}_m\}$  are sequences in  $M$  such that  $\lim_{m \rightarrow \infty} \sup \wp(\check{a}_m, \check{a}) \leq r$ ,  $\lim_{m \rightarrow \infty} \sup \wp(\check{b}_m, \check{a}) \leq r$ , and  $\lim_{m \rightarrow \infty} \wp((1 - t_m)\check{a}_m \oplus t_m\check{b}_m, \check{a}) = r$  for some  $r \geq 0$ . Then

$$\lim_{m \rightarrow \infty} \wp(\check{a}_m, \check{b}_m) = 0.$$

**Lemma 2.6.** ((25)) Let  $\{\alpha_m\}, \{\beta_m\}$  and  $\{\zeta_m\}$  be the sequences of nonnegative numbers such that

$$\alpha_{m+1} \leq (1 + \beta_m)\alpha_m + \zeta_m$$

For all  $m \geq 1$ .  $\sum_{m=1}^{\infty} \beta_m < \infty$  and  $\sum_{m=1}^{\infty} \zeta_m < \infty$ , then  $\lim_{m \rightarrow \infty} \alpha_m$  exists. Whenever, if  $\exists$  a subsequence  $\{\alpha_{m_k}\} \subseteq \{\alpha_m\}$  such that  $\alpha_{m_k} \rightarrow 0$  as  $k \rightarrow \infty$ , then  $\lim_{m \rightarrow \infty} \alpha_m = 0$ .

### 3 Main result

**Theorem 3.1.** Let  $\Theta$  be a closed bounded and convex subset of  $M$ , a complete CAT(0) space and  $S: \Theta \rightarrow \Theta$  is uniformly  $L$ -Lipschitzian and  $(\{\mu_m\}, \{\varkappa_m\}, \varphi)$ -total asymptotically nonexpansive mapping. Assume that the following conditions hold:

- (a)  $\sum_{m=1}^{\infty} \mu_m < \infty$  and  $\sum_{m=1}^{\infty} \varkappa_m < \infty$ ;
- (b)  $\exists$  constants  $\check{m}, \check{n}$  with  $0 < \check{m} \leq \gamma_m \leq \check{n} < 1 \forall m \in N$ .
- (c)  $\exists$  constants  $\check{p}, \check{q}$  with  $0 < \check{p} \leq \beta_m \leq \check{q} < 1 \forall m \in N$ .
- (d)  $\exists$  constants  $\check{l}, \check{o}$  with  $0 < \check{l} \leq \alpha_m \leq \check{o} < 1 \forall m \in N$ .
- (e)  $\exists$  constants  $M^*$  such that  $\varphi(\check{w}) \leq M^* \check{w} \forall \check{w} \geq 0$ .

Then the sequence  $\{e_m\}$  defined by  $\Delta$ -converges to a point of  $F(S) = \{\check{x} \in \Theta: S(\check{x}) = \check{x}\}$  is the set of fixed point.

*Proof.* By using Lemma 2.5, we have  $F(S) \neq \emptyset$ . We begin by demonstrating that  $\lim_{m \rightarrow \infty} \wp(e_m, \rho)$  exists for any  $\rho \in F(S)$ , where  $\{e_m\}$  is defined by (1.7). Let  $\rho \in F(S)$ . Then we have

$$\begin{aligned} \wp(h_m, \rho) &= \wp(S^m((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho). \\ &\leq \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho) \\ &\quad + \mu_m \varphi \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) [(1 - \gamma_m) \wp(e_m, \rho) + \gamma_m S^m \wp(e_m, \rho)] + \varkappa_m. \tag{3.1} \\ &\leq (1 + \mu_m M^*) [(1 - \gamma_m) \wp(e_m, \rho) + \mu_m \varphi \wp(e_m, \rho)) \\ &\quad + \varkappa_m] + \varkappa_m. \\ &\leq (1 + \mu_m M^*) [(1 + \mu_m M^*) \wp(e_m, \rho)] + \varkappa_m + \varkappa_m. \\ &\leq (1 + \mu_m M^*)^2 \wp(e_m, \rho) + (2 + \mu_m M^*) \varkappa_m. \end{aligned}$$

$\forall m \in N$  using (3.1). We have

$$\begin{aligned}
 \wp(g_m, \rho) &= \wp(S^m((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho). \\
 &\leq \wp((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho) \\
 &\quad + \mu_m \wp \wp((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho) + \varkappa_m. \\
 &\leq (1 + \mu_m M^*) \wp((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho) + \varkappa_m. \\
 &\leq (1 + \mu_m M^*) [(1 - \beta_m) \wp(h_m, \rho) + \mu_m \wp \wp(h_m, \rho)) \\
 &\quad + \varkappa_m] + \varkappa_m. \tag{3.2} \\
 &\leq (1 + \mu_m M^*) [(1 + \mu_m M^*) \wp(h_m, \rho) + \varkappa_m] + \varkappa_m. \\
 &\leq (1 + \mu_m M^*)^2 \wp(h_m, \rho) + (2 + \mu_m M^*) \varkappa_m. \\
 &\leq (1 + \mu_m M^*)^2 [(1 + \mu_m M^*)^2 \wp(e_m, \rho) + (2 + \mu_m M^*) \varkappa_m] \\
 &\quad + (2 + \mu_m M^*) \varkappa_m. \\
 &\leq (1 + \mu_m M^*)^4 \wp(e_m, \rho) + [1 + (1 + \mu_m M^*)^2] (2 + \mu_m M^*) \varkappa_m.
 \end{aligned}$$

$\forall m \in N$  using (3.2). Also we have

$$\begin{aligned}
 \wp(f_m, \rho) &= \wp(S^m((1 - \alpha_m)g_m \oplus \alpha_m S^m g_m), \rho). \\
 &\leq \wp((1 - \alpha_m)g_m \oplus \alpha_m S^m g_m), \rho) \\
 &\quad + \mu_m \wp \wp((1 - \alpha_m)g_m \oplus \alpha_m S^m g_m), \rho) + \varkappa_m. \\
 &\leq (1 + \mu_m M^*) \wp((1 - \alpha_m)g_m \oplus \alpha_m S^m g_m), \rho) + \varkappa_m. \\
 &\leq (1 + \mu_m M^*) [(1 - \alpha_m) \wp(g_m, \rho) + \mu_m \wp \wp(g_m, \rho)) \\
 &\quad + \varkappa_m] + \varkappa_m. \tag{3.3} \\
 &\leq (1 + \mu_m M^*) [(1 + \mu_m M^*) \wp(g_m, \rho) + \varkappa_m] + \varkappa_m. \\
 &\leq (1 + \mu_m M^*)^2 \wp(g_m, \rho) + (2 + \mu_m M^*) \varkappa_m. \\
 &\leq (1 + \mu_m M^*)^2 [(1 + \mu_m M^*)^4 \wp(e_m, \rho) \\
 &\quad + [1 + (1 + \mu_m M^*)^2] (2 + \mu_m M^*) \varkappa_m] + (2 + \mu_m M^*) \varkappa_m. \\
 &\leq (1 + \mu_m M^*)^6 \wp(e_m, \rho) \\
 &\quad + (1 + \mu_m M^*)^2 [1 + (1 + (1 + \mu_m M^*)^2)] (2 + \mu_m M^*) \varkappa_m.
 \end{aligned}$$

$\forall m \in N$ . From(1.7), (3.1), (3.2) and (3.3), we get

$$\begin{aligned}
 \wp(e_{m+1}, \rho) &= \wp(S^m f_m, \rho). \\
 &\leq \wp(f_m, \rho) + \mu_m \wp \wp(f_m, \rho) + \varkappa_m. \\
 &\leq (1 + \mu_m M^*) \wp(f_m, \rho) + \varkappa_m. \\
 &\leq (1 + \mu_m M^*) [(1 + \mu_m M^*)^6 \wp(e_m, \rho) \\
 &\quad + (1 + \mu_m M^*)^2 (1 + (1 + ((1 + \mu_m M^*)^2)) (2 + \mu_m M^*) \varkappa_m] + \varkappa_m. \tag{3.4} \\
 &\leq (1 + \mu_m M^*)^7 \wp(e_m, \rho) \\
 &\quad + [1 + (1 + \mu_m M^*)^3 (1 + (1 + ((1 + \mu_m M^*)^2)) (2 + \mu_m M^*) \varkappa_m].
 \end{aligned}$$

Where

$$\eta_m := (1 + \mu_m M^*)^7 \text{ and } \xi_m := 1 + (1 + \mu_m M^*)^3 (2 + \mu_m M^*) (1 + (1 + ((1 + \mu_m M^*)^2))).$$

By assumption (a), we have

$$\sum_{m=1}^{\infty} \eta_m < \infty \text{ and } \sum_{m=1}^{\infty} \xi_m < \infty. \tag{3.5}$$

By assertion (3.4), (3.5) and Lemma 2.6, we obtain  $\lim_{m \rightarrow \infty} \wp(e_m, \rho)$  exists.

Next, we prove that  $\lim_{m \rightarrow \infty} \wp(e_m, S^m e_m) = 0$ .

Without loss of generality we may suppose that

$$\lim_{m \rightarrow \infty} \wp(e_m, \rho) = \check{w} \geq 0. \tag{3.6}$$

From (3.1), we have

$$\lim_{m \rightarrow \infty} \sup \wp(h_m, \rho) \leq \check{w}. \tag{3.7}$$

Since  $S$  satisfies Definition 1.2

$$\begin{aligned} \wp(S^m h_m, \rho) &\leq \wp(h_m, \rho) + \mu_m \wp(h_m, \rho) + \varkappa_m. \\ \wp(S^m h_m, \rho) &\leq (1 + \mu_m M^*) \wp(h_m, \rho) + \varkappa_m. \end{aligned} \tag{3.8}$$

From (3.7) and (3.8), we have

$$\lim_{m \rightarrow \infty} \sup \wp(S^m h_m, \rho) \leq \check{w}. \tag{3.9}$$

In the same way, we get

$$\lim_{m \rightarrow \infty} \sup \wp(S^m e_m, \rho) \leq \check{w}. \tag{3.10}$$

Since

$$\begin{aligned} \wp(e_{m+1}, \rho) &\leq (1 + \mu_m M^*)^7 \wp(e_m, \rho) \\ &\quad + [1 + (1 + \mu_m M^*)^3 (1 + (1 + (\mu_m M^*)^2)) (2 + \mu_m M^*)] \varkappa_m. \end{aligned}$$

By taking limit infimum both sides, we obtain,

$$\check{w} \leq \lim_{m \rightarrow \infty} \inf \wp(h_m, \rho). \tag{3.11}$$

By using (3.7) and (3.11), we have

$$\check{w} = \lim_{m \rightarrow \infty} \sup \wp(h_m, \rho) \leq \lim_{m \rightarrow \infty} \sup \wp(S^m((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho). \tag{3.12}$$

$$\begin{aligned} \wp(S^m((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho) &\leq \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho) \\ &\quad + \mu_m \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho) + \varkappa_m. \\ \lim_{m \rightarrow \infty} \sup \wp(S^m((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), \rho) &\leq \lim_{m \rightarrow \infty} \sup \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho). \\ \check{w} &\leq \lim_{m \rightarrow \infty} \sup \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho). \end{aligned} \tag{3.13}$$

By using (3.6) and (3.10), we have

$$\wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho) \leq ((1 - \gamma_m)\wp(e_m, \rho) + \gamma_m \wp(S^m e_m, \rho)).$$

By taking limit supremum both sides, we obtain

$$\lim_{m \rightarrow \infty} \sup \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho) \leq \check{w}. \tag{3.14}$$

Applying (3.13) and (3.14), we have,

$$\lim_{m \rightarrow \infty} \sup \wp((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, \rho) = \check{w}. \tag{3.15}$$

By using (3.6), (3.10), (3.15) and Lemma 2.5, we can conclude that

$$\lim_{m \rightarrow \infty} \wp(e_m, S^m e_m) = 0. \tag{3.16}$$

We also have,

$$\begin{aligned}\varphi(e_{m+1}, \rho) &\leq (1 + \mu_m M^*)\varphi(f_m, \rho) + \varkappa_m. \\ \varphi(e_{m+1}, \rho) &\leq (1 + \mu_m M^*)[(1 + \mu_m M^*)^2\varphi(g_m, \rho) + (2 + \mu_m M^*)\varkappa_m] + \varkappa_m. \\ \varphi(e_{m+1}, \rho) &\leq (1 + \mu_m M^*)^3\varphi(g_m, \rho) + [1 + (1 + \mu_m M^*)(2 + \mu_m M^*)]\varkappa_m.\end{aligned}$$

By taking limit infimum both sides, we obtain

$$\check{w} \leq \lim_{m \rightarrow \infty} \inf \varphi(g_m, \rho). \quad (3.17)$$

$$\varphi(g_m, \rho) \leq (1 + \mu_m M^*)^4\varphi(e_m, \rho) + [1 + (1 + \mu_m M^*)^2](2 + \mu_m M^*)\varkappa_m.$$

By taking limit supremum both sides, we obtain

$$\lim_{m \rightarrow \infty} \sup \varphi(g_m, \rho) \leq \check{w}. \quad (3.18)$$

By using (3.17) and (3.18), we get

$$\check{w} = \lim_{m \rightarrow \infty} \sup \varphi(g_m, \rho) = \lim_{m \rightarrow \infty} \sup \varphi(S^m((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho). \quad (3.19)$$

$$\begin{aligned}\varphi(S^m((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho) &\leq \varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho) \\ &\quad + \mu_m \varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)\varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho) + \varkappa_m. \\ \lim_{m \rightarrow \infty} \sup \varphi(S^m((1 - \beta_m)h_m \oplus \beta_m S^m h_m), \rho) &\leq \lim_{m \rightarrow \infty} \sup \varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho). \\ \check{w} &\leq \lim_{m \rightarrow \infty} \inf \varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho).\end{aligned} \quad (3.20)$$

Also we have

$$\varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho) \leq (1 - \beta_m)\varphi(h_m, \rho) + \beta_m\varphi(S^m h_m, \rho).$$

By taking limit supremum both sides, we obtain

$$\lim_{m \rightarrow \infty} \sup \varphi((1 - \beta_m)h_m \oplus \beta_m S^m h_m, \rho) \leq \check{w}. \quad (3.21)$$

By using (3.9), (3.12), (3.21) and Lemma 2.5, we can conclude that

$$\lim_{m \rightarrow \infty} \varphi(h_m, S^m h_m) = 0. \quad (3.22)$$

Since  $S$  is  $(\{\mu_m\}, \{\varkappa_m\}, \varphi)$ -total asymptotically nonexpansive mapping.

$$\begin{aligned}\varphi(S^m h_m, S^m e_m) &\leq \varphi(h_m, e_m) + \mu_m \varphi(h_m, e_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)\varphi(h_m, e_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)\varphi(S^m((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), e_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)\varphi(S^m((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m), S^m e_m) \\ &\quad + (1 + \mu_m M^*)\varphi(S^m e_m, e_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)[\varphi((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, e_m) \\ &\quad + \mu_m M^* \varphi((1 - \gamma_m)e_m \oplus \gamma_m S^m e_m, e_m) + \varkappa_m] \\ &\quad + (1 + \mu_m M^*)\varphi(S^m e_m, e_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)^2[\gamma_m \varphi(S^m e_m, e_m)] + (1 + \mu_m M^*)\varphi(S^m e_m, e_m) \\ &\quad + (2 + \mu_m M^*)\varkappa_m. \quad \forall n \in N.\end{aligned} \quad (3.23)$$

By taking limit  $m \rightarrow \infty$  and using (3.16), we get

$$\lim_{m \rightarrow \infty} \wp(S^m h_m, S^m e_m) = 0. \tag{3.24}$$

We have

$$\begin{aligned} \wp(S^m g_m, S^m h_m) &\leq \wp(g_m, h_m) + \mu_m \wp \wp(g_m, h_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) \wp(g_m, h_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) \wp(S^m((1 - \beta_m)h_m \oplus \beta_m S^m h_m), h_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) \wp(S^m((1 - \beta_m)h_m \oplus \beta_m S^m h_m), S^m h_m) \\ &\quad + (1 + \mu_m M^*) \wp(S^m h_m, h_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*) [\wp((1 - \beta_m)h_m \oplus \beta_m S^m h_m, h_m) \\ &\quad + \mu_m M^* \wp((1 - \beta_m)h_m \oplus \beta_m S^m h_m, h_m) + \varkappa_m] \\ &\quad + (1 + \mu_m M^*) \wp(S^m h_m, h_m) + \varkappa_m. \\ &\leq (1 + \mu_m M^*)^2 [\beta_m \wp(S^m h_m, h_m)] + (1 + \mu_m M^*) \wp(S^m h_m, h_m) \\ &\quad + (2 + \mu_m M^*) \varkappa_m. \end{aligned} \tag{3.25}$$

$\forall n \in N..$

By taking limit  $m \rightarrow \infty$  and using (3.22), we get

$$\lim_{m \rightarrow \infty} \wp(S^m g_m, S^m h_m) = 0. \tag{3.26}$$

From (3.16),(3.24) and (3.26), we get

$$\begin{aligned} \wp(e_m, e_{m+1}) &\leq \wp(e_m, S^m e_m) + \wp(S^m e_m, S^m h_m) + \wp(S^m h_m, S^m g_m) \\ &\rightarrow 0 \text{ as } m \rightarrow \infty. \end{aligned} \tag{3.27}$$

Since  $S$  satisfies Definition 1.2 and uniformly  $L$ -Lipshitzian, we obtain

$$\begin{aligned} \wp(e_m, S e_m) &= \wp(e_m, e_{m+1}) + \wp(e_{m+1}, S^{m+1} e_{m+1}) \\ &\quad + \wp(S^{m+1} e_{m+1}, S^{m+1} e_m) + \wp(S^{m+1} e_m, S e_m). \\ &\leq \wp(e_m, e_{m+1}) + \wp(e_{m+1}, S^{m+1} e_{m+1}) + L \wp(e_{m+1}, e_m) \\ &\quad + L \wp(S^m e_m, e_m) \\ &\rightarrow 0 \text{ as } m \rightarrow \infty. \end{aligned} \tag{3.28}$$

Let  $\check{x} \in W_\Delta(e_m)$ . Then,  $\exists$  a subsequence  $\{\check{z}_m\}$  of  $\{e_m\}$  such that  $\mathcal{A}(\{\check{z}_m\}) = \{\check{x}\}$ . By using Lemma 2.3,  $\exists$  a subsequence  $\{\check{y}_m\}$  of  $\{\check{z}_m\}$  such that  $\{\check{y}_m\}$   $\Delta$ -converges to  $\check{y} \in \Theta$ . By Lemma 2.4,  $\check{y} \in F(S)$ . Since  $\{\wp(\check{z}_m, \check{y})\}$  converges, by Lemma 2.2,  $\check{x} = \check{y}$ . This implies that  $W_\Delta(e_m) \subseteq F(S)$ . Next we will prove that  $W_\Delta(e_m)$  consists of exactly one point. Let  $\{\check{z}_m\}$  be a subsequence of  $\{e_m\}$  with  $\mathcal{A}(\{\check{z}_m\}) = \{\check{x}\}$  and  $\mathcal{A}(\{e_m\}) = \{e\}$ . We have seen that  $\check{x} = \check{y}$  and  $\check{y} \in F(S)$ . Finally, since  $\{\wp(e_m, \check{y})\}$  converges, by Lemma 2.2, we have  $e = \check{y} \in F(S)$ . This shows that  $W_\Delta(e_m) = \{e\}$ .  $\square$

**Theorem 3.2.** *Let  $M, S, \Theta, (a), (b), (c), (d), (e), \{\gamma_m\}, \{\beta_m\}$  and  $\{\alpha_m\}$  same as in Theorem 3.1. Then, the sequence  $\{e_m\}$ , defined by (1.7) strongly converges to a fixed point of  $S$  iff*

$$\lim_{m \rightarrow \infty} \inf \wp(e_m, F(S)) = 0.$$

where  $\wp(\check{x}, F(S)) = \inf \{\wp(\check{x}, \rho) : \rho \in F(S)\}$ .

*Proof.* Necessity is obvious. Conversely, suppose that  $\lim_{m \rightarrow \infty} \inf \wp(e_m, F(S)) = 0$ . As proved in Theorem 3.1,  $\lim_{m \rightarrow \infty} \wp(e_m, F(S))$  exists for all  $\rho \in F(S)$ . Thus, by hypothesis,  $\lim_{m \rightarrow \infty} \wp(e_m, F(S)) = 0$ .

Next, we show that  $\{e_m\}$  is cauchy sequence in  $C$ . Let  $\epsilon > 0$  be arbitrary Chosen. Since  $\lim_{m \rightarrow \infty} \wp(e_m, F(S)) = 0$ ,  $\exists$  a positive integer  $m_0$  such that for all  $m \geq m_0$ ,

$$\wp(e_m, F(S)) < \frac{\epsilon}{4}.$$

In particular,  $\inf\{\wp(e_{m_0}, \rho) : \rho \in F(S)\} < \frac{\epsilon}{2}$ . Thus,  $\exists \rho^* \in F(S)$  such that

$$\wp(e_{m_0}, \rho^*) < \frac{\epsilon}{2}.$$

Now, for all  $m, k \geq m_0$ , we have

$$\wp(e_{m+k}, e_m) \leq \wp(e_{m+k}, \rho^*) + \wp(e_m, \rho^*) \leq 2\wp(e_{m_0}, \rho^*) < 2\left(\frac{\epsilon}{2}\right) = \epsilon.$$

i.e.,  $\{e_m\}$  is a cauchy sequence in the closed subset  $\Theta$  of a complete CAT(0) space and hence it converges to a point  $q$  in  $\Theta$ . Now  $\lim_{m \rightarrow \infty} \wp(e_m, F(S)) = 0$  gives that  $\wp(q, F(S)) = 0$  and closedness of  $F(S)$  forces  $q$  to be in  $F(S)$ . This completes the proof.  $\square$

Senter and Dotson (27) introduced a mapping satisfy the condition (I) as follows:

**Definition 3.1.** A mapping  $S: \Theta \rightarrow \Theta$  is said to satisfy the Condition (I) ((27)) if  $\exists$  a nondecreasing function  $f: [0, \infty) \rightarrow [0, \infty)$  with  $f(0) = 0$  and  $f(w) > 0$  for all  $w \in (0, \infty)$  such that  $\wp(e, Se) \leq f(\wp(e, F(S)))$  for all  $e \in \Theta$ ; where  $\wp(e, F(S)) = \inf\{\wp(e, \rho) : \rho \in F(S)\}$ .

By using the similar technique as in the proof of Theorem 3.3 by Thakur et. al (29), we get the following result:

**Theorem 3.3.** Let  $M, S, \Theta, (a), (b), (c), (d), (e), \{\gamma_m\}, \{\beta_m\}$  and  $\{\alpha_m\}$  satisfy the hypothesis of theorem 3.1 and let  $S$  be a mapping satisfying Condition (I). Then the sequence  $\{e_m\}$  generated by (1.7) converges strongly to a fixed point of  $S$ .

*Proof.* As proved in theorem 3.2,  $\lim_{m \rightarrow \infty} \wp(e_m, F(S))$  exists. Also, by the theorem 3.1, we have  $\lim_{m \rightarrow \infty} \wp(e_m, Se_m) = 0$ . It follows from Condition (I) that

$$\lim_{m \rightarrow \infty} f(\wp(e_m, F(S))) \leq \lim_{m \rightarrow \infty} \wp(e_m, Se_m) = 0.$$

That is,  $\lim_{m \rightarrow \infty} f(\wp(e_m, F(S))) = 0$ . Since  $f: [0, \infty) \rightarrow [0, \infty)$  is a non-decreasing function satisfying  $f(0) = 0$  and  $f(r) > 0$  for all  $r > 0$ , we obtain

$$\lim_{m \rightarrow \infty} \wp(e_m, F(S)) = 0.$$

Now all the conditions of Theorem 3.4 are satisfied, therefore by its conclusion  $\{e_m\}$  converges strongly to a point of  $F(S)$ .  $\square$

**Theorem 3.4.** Let  $M, S, \Theta, (a), (b), (c), (d), (e), \{\gamma_m\}, \{\beta_m\}$  and  $\{\alpha_m\}$  be same as in Theorem 3.1 with  $S$  satisfies Condition(I). Then,  $\{e_m\}$ , defined by (1.7) converges to a point of  $F(S)$ .

*Proof.* Recalling the definition of semi-compact mapping;

A map  $S$  defined on  $\Theta$  is said to be semi-compact (28) if for a sequence  $\{e_m\}$  in  $\Theta$  with  $\lim_{m \rightarrow \infty} \wp(e_m, Se_m) = 0$ ,  $\exists$  a subsequence  $\{e_{m_j}\}$  of  $\{e_m\}$  such that  $e_{m_j} \rightarrow \rho \in \Theta$ .

By using the same steps used by Karapinar et al. (16) in the proof of Theorem 22, we get the next result.  $\square$

**Corollary 3.1.** Let  $M, S, \Theta, (a), (b), (c), (d), (e), \{\gamma_m\}, \{\beta_m\}$  and  $\{\alpha_m\}$  be same as in Theorem 3.1. Let  $S$  be semi-compact. Then the sequence  $\{e_m\}$  defined by (1.7) converges to a point of  $F(S)$ .

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## 4 Numerical example

In this part, we'll look at a total asymptotically nonexpansive mapping as an example.

Let  $M = \mathbb{R}$  with usual metric and  $C = [0, 2]$ . Let a self map  $S$  on  $\Theta$  as follows:

$$Sx = \begin{cases} 1, & x \in [0, 1]; \\ \frac{1}{\sqrt{3}}\sqrt{4-x^2}, & x \in [1, 2]. \end{cases}$$

Here  $S$  is a uniformly continuous and total asymptotically nonexpansive mapping with  $F(S) = \{1\}$ . Also satisfies Condition (I), but  $S$  is not Lipschitzian and hence it is not an asymptotically nonexpansive mapping.

## 5 Conclusion

In this paper, we have presented a new type of iteration procedure for total asymptotically nonexpansive mapping in CAT(0) spaces. Our result generalizes results of Thakur et al. (29) and Izhhar et al. (30) in the sense of faster iteration process.

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